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By

JOHN KELLOCK ROBERTSON F.R.S.C.

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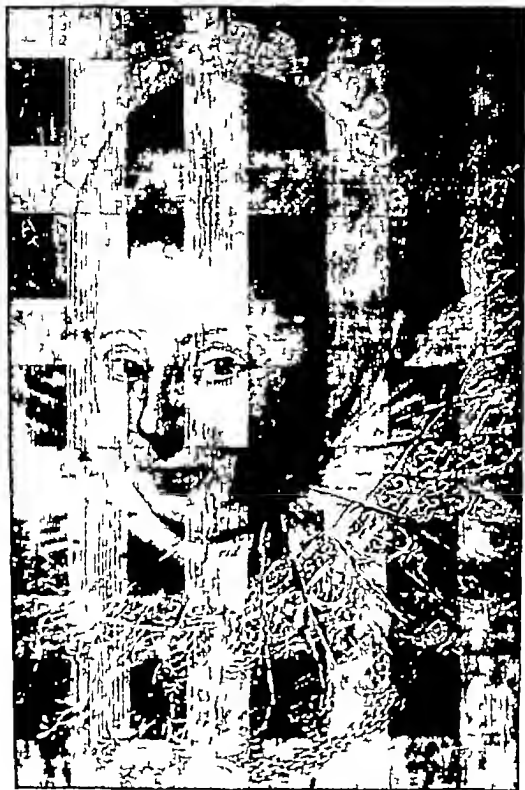
RADIOLOGY PHYSICS

An Introductory Course for Medical or Premedical Students and for all Radiologists.

PUBLISHED BY

D. VAN NOSTRAND COMPANY INC.
NEW YORK

Radiology Physics



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Radiology Physics

AN INTRODUCTORY COURSE FOR MEDICAL OR PREMEDICAL
STUDENTS AND FOR ALL RADIOLOGISTS

By

JOHN KELLOCK ROBERTSON, F.R.S.C.

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LONDON
CHAPMAN & HALL, LTD
11 HENRIETTA STREET, W C 2

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*First Published January 1941
Reprinted July 1943*

Printed in U. S. A.

Printing
F. H. GILSON CO.
BOSTON

Composition
TECHNICAL COMPOSITION CO.
BOSTON

Binding
STANBROOK BOOKS
BOSTON

To
my wife

PREFACE

With the ever increasing applications of physics in medicine the problem of giving the medical or the premedical student adequate instruction in physics has become one which demands action. To teach in one year the fundamental principles of physics, and at the same time to deal adequately with those applications with which a medical student should be familiar is well nigh impossible. At Queen's University the problem has been solved and, on the whole satisfactorily by giving instruction in two successive years. In the first year the student is given the usual course in general physics, with the omission of electricity and magnetism. In the second year lectures and laboratory work in electricity and magnetism lead naturally to a consideration of such topics as x ray transformers, x ray tubes, conduction of electricity through gases, radioactivity nuclear physics, and high frequency currents. RADIOLOGY PHYSICS covers, with some amplification the work given by the author in the second half of this course.

It is hoped that this book will prove suitable as a text for similar courses elsewhere, especially for those institutions which agree with the Committee on the Teaching of Physics for Premedical Students* in their opinion that the American Association of Physics Teachers should go on record as in favour of making the physics prerequisite two years instead of one. RADIOLOGY PHYSICS is also commended to all radiologists and radiological technicians who wish, not a handbook, but a simple explanation of the physical principles underlying the use of their apparatus. Although a knowledge of elementary electricity and magnetism is assumed, the mathematical treatment is reduced to a minimum.

In the preparation of the manuscript, the author has made some use of an earlier book on *X-rays and X ray Apparatus* and his thanks are due the President of D. Van Nostrand Company Inc., for permission to use some of the material in the more recent *Atomic Artillery*. Under each illustration due acknowledgment is made where necessary but my special thanks are due the Philips Gloeilampenfabrieken Eindhoven Holland, the General Electric X ray Corporation Dr. J. G. Trump of the Massachusetts Institute of Technology and Mrs. Edith Qumby and Dr. G. Failla of the Memorial Hospital, New York, for photographs and other material. Acknowledgment

* The American Physics Teacher 5 267 1937

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is also made of the kindness of Mr A. C. Baldwin, Mr G. E. Simons, and Dr J. Gross, of the General Electric Corporation, and Mr Victor Hicks of the Westinghouse X Ray Company

It is a pleasure to thank my wife for her valuable assistance throughout the preparation of the book, and my colleagues Dr B. W. Sargent, who read part of the manuscript, and Dr H. W. Harkness, who read the chapters on high voltage. With Dr Sargent the author has had many discussions. My friend and colleague Dean A. L. Clark has again provided clerical and other assistance and it is a pleasant duty to express to him my appreciation

J. K. R.

QUEEN'S UNIVERSITY
KINGSTON CANADA
October, 1940

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CHAPTER I

ALTERNATING CURRENTS

The aim of this text is to present in a systematic way the fundamental physical principles utilized in the field of radiology. It is assumed that the reader has had a general course in physics such as is given in the first year of liberal arts or to premedical students, but the author does not hesitate to review and to amplify important parts of the elementary course. For example at the outset the student is asked to recall a few principles in electricity and magnetism that branch of physics whose applications abound in radiology.

1 Electromagnetism. — All students are familiar with the fact that when a bar magnet is placed beneath a sheet of paper on which iron filings are sprinkled, the filings arrange themselves along regular lines. This simple experiment indicates that in the region around the magnet there is a *magnetic field of force*. To visualize this field we say that it is traversed by magnetic lines of force the actual number of lines being so chosen that at any particular place, the *intensity* or strength of the magnetic field is equal to the number of lines passing through an area of 1 sq. cm., the area being at right angles to the direction of the lines. A field of unit intensity it will be recalled, is equal to 1 dyne per unit pole and is called 1 *oersted*.



FIG. 1 Lines of Force are linked with a solenoidal coil carrying a current.

These lines of force are closed curves which leave the north pole of the magnet and enter the south constituting what is called a *magnetic flux* through the magnet. Indeed, whenever magnetic lines pass through any region, we speak of a magnetic flux through that region.

Elementary experiments with electric currents prove that a magnetic field surrounds a wire carrying a current and show that if the wire is bent into a solenoidal coil as in Fig. 1 one end of the solenoid is a north pole the other a south. Moreover if the air inside the solenoid is replaced by a core of soft

iron, the iron becomes strongly magnetized under the influence of the magnetic field due to the current, and a powerful electromagnet may be created. We can have magnetic fields, therefore, subject to the control of an electric circuit. When the circuit is closed, the magnetic lines are said to be *linked* with the turns of the circuit, the number of *linkages* being equal to the product of the total magnetic flux times the number of turns of the circuit with which they are linked. When the circuit is broken, the lines disappear, with a consequent change in the number of linkages.

2 Electromagnetic Induction.— Suppose a wire *AB*, Fig 2, which forms part of a simple closed circuit containing a galvanometer *G* but no

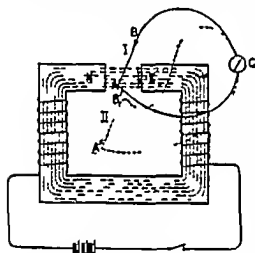


FIG. 2. When the wire *AB* is moved across the magnetic field, an induced electromotive force is developed in the wire.

battery is free to be moved between the poles of an electromagnet whose circuit is closed. If *AB* is moved from position I across the lines of force to position II, (indicated by *AB*) a momentary current is indicated by the galvanometer. If the wire *AB* is moved back again, a momentary current in the opposite direction is recorded. In general, it is found that as long as the wire is moving with respect to the lines of force, a current is developed. This and many other similar experiments prove that *whenever a portion of any circuit is moving with respect to magnetic lines of force an induced electromotive force (E.M.F.) is developed and if the circuit is closed, an induced current results.*

This is the very important principle of electromagnetic induction, discovered in 1832 by Faraday in England, and simultaneously by Henry in the United States.

The principle may be stated in another and possibly more useful way. When the movable wire *AB* is in position I there are no lines of force linked with the galvanometer circuit, but when it is in position II all the lines are linked or interlocked with that circuit. Frequently then, we state that an induced E.M.F. is developed in a circuit wherever there is any *change* in the number of lines linked with it. If for example, the wire is left in position *AB'* and the electromagnet circuit (the *primary* circuit) is *broken*, there is a momentary induced current in the movable wire circuit (the *secondary*). Again, when the primary circuit is *made* a momentary induced current results

in the secondary In this experiment, the secondary circuit is not moved, but the magnetic lines appear on make of the primary disappear on break, and so on both make and break there is relative motion of lines and a portion of a circuit. Or stating it the other way, on *break* of the primary there is a decrease in the number of lines linked with the secondary; on *make* an increase — in both a change, and hence an induced E.M.F. is developed.

The magnitude of the induced E.M.F. is found by experiment to depend on the *rate* at which the lines are cut or on the rate at which the number of linkages is changing. Large E.M.F. may be obtained therefore, when numerous electric conductors rapidly cut the lines of strong magnetic fields, or when such fields are linked and "unlinked" with many turns of an electric circuit. This, in fact, is the basic principle utilized in dynamos, in transformers and in induction coils.

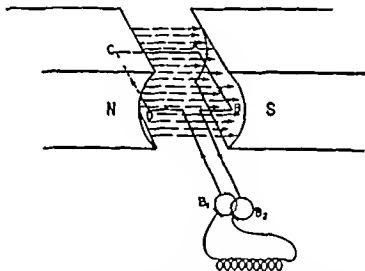


FIG. 3. A simple arrangement to generate an alternating current.

3 Alternating Currents (A.C.) — Suppose a single loop of wire *ABCD* Fig 3 is rotated in the region between two magnetic poles *N* and *S*. As the wire *AB* goes down it cuts lines of force and in it we have an induced E.M.F. in the direction of the arrow. At the same time *CD* the other side of the loop goes up thus cutting the lines in the opposite direction and so developing in *CD* an induced E.M.F. in the opposite direction. If the ends of the loop are connected to two slip rings upon which rest brushes *B₁* and *B₂* and these brushes are connected by an external conductor the circuit is complete and a current flows. Evidently all the time *AB* is going down and *CD* up, that is, for half a revolution a current flows in the direction indicated by the arrows. After *AB* has reached its lowest position however it begins to

iron, the iron becomes strongly magnetized under the influence of the magnetic field due to the current, and a powerful electromagnet may be created. We can have magnetic fields, therefore, subject to the control of an electric circuit. When the circuit is closed, the magnetic lines are said to be *linked* with the turns of the circuit, the number of *linkages* being equal to the product of the total magnetic flux times the number of turns of the circuit with which they are linked. When the circuit is broken, the lines disappear, with a consequent change in the number of linkages.

2. Electromagnetic Induction. — Suppose a wire AB , Fig 2, which forms part of a simple closed circuit containing a galvanometer G but no battery, is free to be moved between the poles of an electromagnet whose circuit is closed.

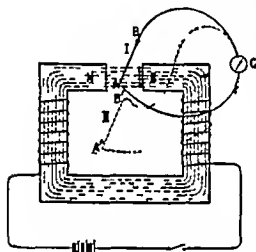


FIG. 2. When the wire AB is moved across the magnetic field, an induced electromotive force is developed in this wire.

If AB is moved from position I across the lines of force to position II, (indicated by AB') a momentary current is indicated by the galvanometer. If the wire AB is moved back again, a momentary current in the opposite direction is recorded. In general, it is found that as long as the wire is moving with respect to the lines of force, a current is developed. This and many other similar experiments prove that *whenever a portion of any circuit is moving with respect to magnetic lines of force an induced electromotive force (E.M.F.) is developed, and if the circuit is closed, an*

induced current results. This is the very important principle of electromagnetic induction, discovered in 1832 by Faraday in England, and simultaneously by Henry in the United States.

The principle may be stated in another and possibly more useful way. When the movable wire AB is in position I there are no lines of force linked with the galvanometer circuit, but when it is in position II all the lines are linked or interlocked with that circuit. Frequently then, we state that an induced E.M.F. is developed in a circuit wherever there is any *change* in the number of lines linked with it. If for example the wire is left in position AB' and the electromagnet circuit (the *primary* circuit) is *broken*, there is a momentary induced current in the movable wire circuit (the *secondary*). Again when the primary circuit is *made* a momentary induced current results

obtained by using several sets of magnet poles, alternately ¹¹⁰north and south, and many loops of wire. The fundamental principles utilized, however are the same as those we have been discussing and the current supplied by such generators generally approximates fairly closely to the sinusoidal

In direct current (D.C.) generators, it is important to realize that the same principles are utilized and that an alternating E.M.F. is developed in the rotating loops or moving conductors. By the use of commutator plates, this alternating current is *rectified* and direct current flows in the external circuit.

4 Strength of A.C. — When alternating currents are used in the laboratory an A.C. ammeter placed in the circuit indicates a definite current of so many amperes. Actually we know that the current is varying in the manner represented by Fig. 4 being sometimes in one direction sometimes in another with magnitude constantly changing. What, then, does the instrument record? To understand the answer to that question, it is necessary to

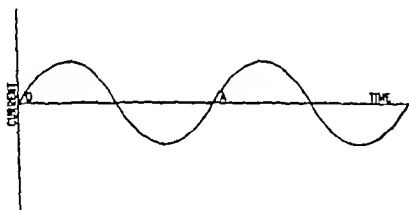


FIG. 4 Graphical representation of a simple alternating current.

know that, by agreement, an alternating current has a value or strength equal to that of a direct current which produces the same heat in a given resistance, in the same time. If for example in a certain time an alternating current in a coil of wire develops the same heat as a direct current of 2 amperes, the alternating current has a strength of 2 amperes. Sometimes the strength is said to be so many *virtual* amperes, but more often the qualifying word is dropped.

The common D.C. ammeter of the moving coil type cannot be used to measure alternating current, because with such a current the coil is acted on by rapid impulses tending to rotate it, first in one direction then in the opposite and no movement except a possible quivering of the pointer is observed. In a

ALTERNATING CURRENTS

move up ^{thus} cutting lines in the opposite direction and the direction of the induced E.M.F. and of the resulting current reverses. At the same time the wire CD reverses its direction from up to down, and in it, too, the induced E.M.F. changes direction. It follows, therefore, that with this simple arrangement, for one half of a revolution a current is flowing in one direction for the other half, in the opposite.

Not only however, is there a reversal of current (or, if you like, of polarity between the brushes B_1 and B_2) but the *strength* of the current is continually changing. This will be evident if it is realized that when the wire AB is passing through its highest position and the wire CD through its lowest, each wire is moving parallel to the magnetic lines and hence for a short interval of time there is no cutting and, therefore, no induced voltage and no current. As AB goes down (and CD up) the lines are cut more and more quickly until after one quarter of a revolution both AB and CD are moving directly at right angles to the lines. At this instant, therefore, the magnetic lines are cut at the fastest rate and the biggest induced voltage results. For the next quarter of a revolution, the lines are cut less and less quickly until AB reaches the bottom (CD the top) and once more, for a brief moment, each wire is moving parallel to the lines, and the voltage has dropped to zero again. Evidently, then, during one complete revolution, the current in the circuit will gradually rise in one direction to a maximum value, drop until it is zero from which it gradually climbs to a maximum in the opposite direction, again falling to zero. If the loop is rotated at steady speed and in a uniform magnetic field, the manner in which the current changes with time is represented graphically in Fig. 4.

A current of this type is an *alternating* one (A.C.) as well as *sinusoidal*. Obviously a sinusoidal current is characterized by (1) changing polarity and (2) gradual "smooth" changes in intensity. (See also section 188.)

It is well to note that while a sinusoidal current is always A.C., it is possible to have alternating currents which are not sinusoidal.

Two or three important terms should be noted.

A *cycle* refers to the complete change from zero to a maximum in one direction, down through zero to a maximum in the other direction and back again to zero. In Fig. 4 OA represents a cycle.

The *frequency* of A.C. is the number of cycles per second. Most householders on the American continent are supplied with A.C. at 110 volts, with a frequency of 60 cycles per second, although as low as 25 is sometimes used.

Neither this voltage nor this frequency could be generated with a simple machine of the type illustrated. In the practical A.C. generators or dynamos or alternators found in power houses, the desired frequency and voltage are

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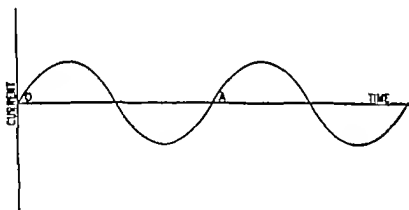


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closing of the circuit, the actual current has a value given by

$$\text{current} = \frac{\text{E.M.F. of battery} - \text{E.M.F. of inductance}}{\text{resistance of circuit}},$$

or, in symbols $I = \frac{E - E'}{R}$, where $E' = \text{E.M.F. of inductance}$.

For this reason the electromagnet current does not immediately attain its final steady value (given by $I = \frac{E}{R}$) but rises somewhat as shown in Fig. 5. Ultimately the number of linkages becomes constant, there is no opposing induced E.M.F. and the current has a constant value.

If the electromagnet circuit is broken the lines of force disappear and if the break is made quickly enough a large E.M.F. of inductance is developed in the same direction as the original applied E.M.F. Its magnitude may be many times greater than that of the original E.M.F., so great, indeed, that a spark jumps the gap where the break is made. This spark may be accompanied by or followed by an arc between the separated metal parts of the breaking switch, an arc which must sometimes be suppressed by the use of special circuit breakers or magnetic blow-outs.

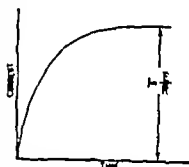


FIG. 5 The rise of a direct current in an inductive circuit.

The effect of inductance may be illustrated in a simple manner by the use of an ordinary dry cell and an electromagnet (or primary of a transformer) of low resistance. If the terminals of the cell are short-circuited by a piece of copper wire and the circuit suddenly broken, no more than an infinitesimal spark or flash is seen at the place of break. If, however, the cell is connected in series with the electromagnet, on break there is a bright flash. Although the current in the first place is actually greater than in the second, the number of magnetic lines linked with the circuit is so small compared with the number in the second that the induced E.M.F. on break is not great enough to cause an appreciable spark. With an electromagnet in the circuit, the number of linkages is increased many times and a marked spark occurs when they disappear on break.

This experiment illustrates the difference between a *noninductive* and an *inductive* circuit. In the former the number of linkages per ampere is so small that the induced E.M.F. on make or on break is negligibly small; in the latter there is a large number of linkages per ampere, with important effects both on make and on break of a direct current. On make there is a delay in

hot wire instrument, however, the movement of the pointer depends on the change in length and tension of a wire heated by a current and this is independent of its direction. Such an instrument, therefore, can be used for measuring both A.C. and D.C. It is, of course, not the only type.

5 Meaning of R.M.S. — The student will recall that the amount of heat developed in a conductor in a given time, depends on the square of the current, or that the power dissipated in a conductor of resistance R is I^2R watts, where I is the current in amperes and R the resistance in ohms. With this in mind it should not be difficult to see that, when alternating current is used, the equivalent direct current is equal to the square root of the average of the squares of successive values, if a complete cycle is subdivided into a large number of intervals. For this reason the strength of an alternating current or the number of virtual amperes is sometimes referred to as the Root Mean Square or R.M.S. value. The same expression may be applied to a similar average of any quantity varying according to the same law as is represented by Fig. 4. Alternating voltmeters, for example, record the R.M.S. value of the alternating E.M.F.

With a little knowledge of calculus, it is not difficult to prove that

$$\text{R.M.S. value} = \frac{\text{maximum value}}{\sqrt{2}}$$

$$\text{or} \quad = 0.707 \text{ maximum value.}$$

Thus, if an A.C. ammeter records 7.07 amperes, we know that the actual current changes from 0 to 10 amperes in each direction.

6 Inductive and Noninductive Circuits. — Suppose a coil of wire is wound around an iron core as in any ordinary electromagnet, and that it is supplied with direct current. Before the circuit is closed the magnetic field is weak or absent altogether and the number of magnetic lines linked with the circuit is negligibly small. After the circuit is closed, however, a strong magnetic field exists, with a corresponding large number of linkages. Therefore during the time immediately following the closing of the circuit, there is a big change in the number of linkages. Consequently while the change is taking place, an induced E.M.F., called an *E.M.F. of inductance*, is developed in the coil of the electromagnet.

Now by Lenz's Law any induced E.M.F. is in a direction opposing the change which gives rise to it. This E.M.F. of inductance, therefore, is in a direction opposite to the original applied voltage, and so immediately after the

the opposing E M F of inductance. Actually the ammeter records about 0.89 amperes. As far as alternating current is concerned, the electromagnet therefore, has an effective resistance of $\frac{110}{0.89}$ or 123.6 ohms. This total resistance to an alternating current is called the *impedance* of the circuit. Its magnitude depends on (1) the true resistance, in this case 50 ohms and (2) the *inductive reactance* the name given to the effective resistance arising from the induced E M F.

Since the magnitude of any induced E M F depends on the rate at which the number of linkages is changing the numerical value of the reactance depends both on the inductance or the number of linkages per ampere and on the frequency of the alternating current. Obviously the higher the frequency the more rapidly the number of linkages is changing. It requires a little more mathematics than is at the disposal of most medical students to prove that the reactance in ohms is equal to $2\pi fL$, where f is the frequency and L the inductance expressed in henries.

For example the reactance of the above electromagnet (whose inductance is 0.3 henry) when an alternating current of 60 cycles per second is used is equal to

$$2\pi \times 60 \times 0.3 \quad \text{or} \quad 113.1 \text{ ohms.}$$

It will be noticed that, although R the true resistance of the electromagnet is 50 ohms and the reactance 113.1 ohms, the impedance is only 123.6 ohms, not the sum of these two numbers. The problem then arises, given the resistance and the reactance, how can we calculate the impedance? The answer is simple, although the proof is not and must be omitted from this text. If we make a right-angle triangle as in Fig. 7 and let the length of one side represent R the resistance, the other side $2\pi fL$ the reactance then the impedance is given by the length of the hypotenuse. It follows at once that the impedance Z is given by the relation

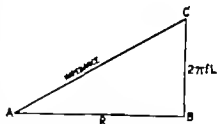


FIG. 7. Triangle showing the magnitude of impedance due to resistance and inductive reactance.

$$Z = \sqrt{R^2 + (2\pi fL)^2}$$

which for the above electromagnet gives us,

$$\begin{aligned} Z &= \sqrt{50^2 + (113.1)^2} \\ &= 123.6 \text{ ohms.} \end{aligned}$$

the rise of the current, whereas on break, an E.M.F., often quite large, is developed. A circuit containing an incandescent lamp is noninductive, one with an electromagnet, inductive.

A circuit has an inductance of 1 henry when the number of linkages per ampere is 10^9 or one hundred million*. For example, if an electromagnet is wrapped with 200 turns of wire and a total flux of 10,000 lines traverses its iron core when the exciting current is 1 ampere, its inductance is

$$\frac{200 \times 10,000}{10^9} \text{ or } \frac{1}{50} \text{ of a henry}$$

7 Impedance and Inductive Reactance.—When an alternating current flows in an inductive circuit, the magnetic field is constantly changing and so opposing induced E.M.F. are present at all times. These have an important effect on the magnitude of the average current in the circuit. Let us examine carefully the difference between an inductive and a noninductive circuit in so far as alternating currents are concerned.

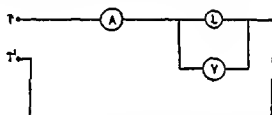


FIG. 6. Simple circuit for measuring resistance for D.C., or impedance for A.C.

Suppose a lamp of resistance 440 ohms is joined in series with an ammeter, suitable for either A.C. or D.C., to supply terminals TT' , as illustrated in

Fig. 6. If the supply voltage is 110 direct, the ammeter reads $\frac{110}{440}$ or 0.25 ampere. If the supply voltage is 110 alternating (that is, an A.C. voltmeter placed across the terminals records 110 volts) the ammeter indicates practically the same reading. In other words, Ohm's Law in its simple form holds for both A.C. and D.C. when we are dealing with a simple noninductive circuit.

Now replace the lamp by an electromagnet of resistance 50 ohms and inductance 0.3 henry. With direct current, the ammeter records $\frac{110}{50}$ or 2.2 amperes. With alternating current, the reading is very much less because of

* On henry is more often defined as the inductance of a circuit such that, when the current is changing at the rate of 1 ampere per second, the induced E.M.F. is 1 volt. The two definitions are of course, equivalent.

ance is called a *capacitative reactance* to distinguish it from inductive reactance.

The value of the capacitative reactance may be calculated from the expression $\frac{1}{2\pi fC}$, where C is the capacity of the condenser expressed in farads.*

Taking the above microfarad condenser as an example we find its reactance to be

$$\frac{1}{2\pi \cdot 60 \cdot 1 \times 10^{-6}} \text{ or } 265 \text{ ohms.}$$

If f is extremely high, as in diathermy or radio circuits, the capacitative reactance is correspondingly small — just the opposite to the reactance of an inductance for such currents. For example for a 100 million cycle per second frequency, the reactance of a microfarad condenser is

$$\frac{1}{2\pi \cdot 100 \times 10^6 \times 1 \times 10^{-6}} \text{ or } \frac{1}{200\pi}$$

or a small fraction of an ohm

9 Combination of Resistance and Capacity

— If a noninductive resistance, a tungsten lamp for example, of resistance R ohms is inserted in series with a condenser and the two are joined to A.C. supply terminals, the impedance of the combination is again found by the use of a right-angle triangle. As illustrated in Fig. 9 if one side of the triangle represents R and the other the capacitative reactance $\frac{1}{2\pi fC}$, the hypotenuse represents the impedance, or, using a formula, the impedance Z of a combination of a non inductive resistance and a condenser is given by

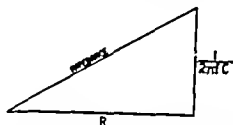


FIG. 9 Triangle showing the magnitude of impedance due to resistance and capacitative reactance.

$$Z = \sqrt{R^2 + \frac{1}{(2\pi fC)^2}} \text{ ohms.}$$

10. Resistance, Capacity and Inductance. — When the alternating circuit includes resistance, capacity and inductance, the impedance of the circuit is given by

$$Z = \sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2}$$

* The student will recall that, when the potential difference between the plates of a condenser of capacity 1 farad is equal to 1 volt, the charge on either plate is 1 coulomb

Not long ago a traveler for scientific apparatus was demonstrating a new light designed to work on 110 A.C. He was mistakenly told that the D.C. supply terminals in a laboratory were A.C. and on plugging in the lamp, immediately found that it burned out. The impedance of the lamp circuit was much greater than its true resistance, hence when D.C. was used, the current was much higher than with A.C.

Sometimes the impedance is due almost entirely to the reactance, as in the case of a *choke coil*. This device consists of a coil of wire of low resistance, with an iron core which may be withdrawn from the coil or whose position may be altered in such a way that the value of L the inductance gradually changes.

In high frequency circuits, which will be discussed in Chapter XVI, the value of the frequency is of the order of a million or a hundred million cycles per second. With such circuits (and we encounter them in radio sets) even a small value of L may correspond to an appreciable or even a high reactance. For example, if $L = 1$ microhenry,* and $f = 10^6$ cycles per sec., the reactance is 2π or 6.28 ohms.

8. Capacitive Reactance.—When a condenser, such as C , Fig. 8, is joined to an ordinary battery or to D.C. terminals TT' , the condenser is

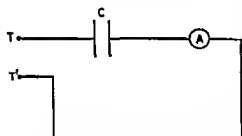


FIG. 8. An ammeter in series with D.C. supply and a condenser indicates no current.

charged, but after a momentary initial current, a good condenser acts as an infinite resistance and an ammeter A placed in the circuit indicates no current. When the condenser is joined to alternating supply terminals, the situation is very different. As the alternating current surges to and fro the condenser is continually charged and discharged, its plates being alternately positive and negative negative and positive, and so on. An A.C. am-

meter placed in the circuit indicates a current just as if it were in an ordinary lighting circuit.

If the condenser has a capacity of 1 microfarad and the alternating supply is 110 volts, 60 cycles per second, the ammeter actually indicates a current of about 0.415 ampere. The condenser therefore, is equivalent to an effective

resistance, or reactance of $\frac{110}{0.415}$ or about 265 ohms. This effective resist

* The student will scarcely need to be reminded that the prefix *micro* means one millionth or 10^{-6} of the main unit.

ance is called a *capacitive reactance*, to distinguish it from inductive reactance.

The value of the capacitive reactance may be calculated from the expression $\frac{1}{2\pi fC}$, where C is the capacity of the condenser expressed in farads.* Taking the above microfarad condenser as an example we find its reactance to be

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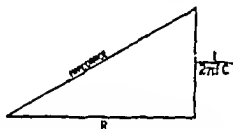


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* The student will recall that, when the potential difference between the plates of a condenser of capacity 1 farad is equal to 1 volt, the charge on either plate is 1 coulomb.

It will be noted that, since in this expression we subtract the two reactances, the impedance may again be found by the use of a right-angle triangle. As before one side represents the value of R , but the length of the other side is now equal to the difference between the inductive and the capacitive reactances. In the special case where the two reactances are exactly equal, they cancel one another and the total impedance reduces to R . If R is small, large currents may be obtained with small alternating E.M.F. We are then dealing with a resonating circuit about which more will be given in Chapter XVI.

11 Phase Difference.—The student will recall that when a direct current of I amperes flows under a potential difference of V volts, the power supplied is VI watts. It might be expected that the same expression could be applied when alternating currents are used. This, however, is by no means always correct. The power is always *proportional* to the product of V the voltage recorded by an A.C. voltmeter times I , the amperage on the A.C.

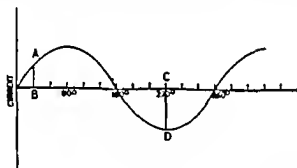


FIG. 10. Graph to illustrate the meaning of phase angle.

ammeter, but it is not always *equal* to this product. To understand why this is so, it is necessary to explain the meaning of *phase*.

In a sinusoidal curve such as we have shown in Fig. 4 and again in Fig. 10 the magnitude at any instant of the changing current (or any other changing variable that the curve represents) can be calculated from the law $I = I_m \sin \theta$, where

I = the magnitude of the current at any instant,

I_m = its maximum value

and θ = an angle whose value steadily increases with the time and changes in one cycle by 360°

Suppose for example, that an alternating current has a maximum value of 10 amperes. Then to obtain the exact shape of the curve which shows how its magnitude changes during one cycle, all that is necessary is to calculate the values of $10 \sin 0^\circ$, $10 \sin 30^\circ$, $10 \sin 60^\circ$ etc. and to plot these values against the corresponding angles. Figure 10 illustrates the plot obtained in such a

manner making use of the numbers given in Table I. Values of θ are taken every 30° for convenience but a still more accurate curve would be obtained by taking angles closer together. Since sine values repeat every 360° the curve between 360° and 720° or 720° and 1080° etc. will be the exact duplicate of that between 0° and 360° .

TABLE I

θ	$\sin \theta$	$10 \sin \theta$
0°	0.00	0
30°	0.500	5.00
60°	0.866	8.66
90°	1.00	10.00
120°	0.866	8.66
150°	0.500	5.00
180°	0.00	0.00
210°	-0.500	-5.00
240°	-0.866	-8.66
270°	-1.00	-10.00
300°	-0.866	-8.66
330°	-0.500	-5.00
360°	0.00	0.00

Now it should be evident that an exact method of describing the particular stage of the cycle which the current (or other variable) has reached at any instant is to give the magnitude of the corresponding angle or what is called the *phase angle*. Thus at a certain instant when there is a positive current of magnitude AB Fig. 10 the phase angle is 30° or when the current has a negative value CD the phase angle is 270° .

Often we are concerned with the phase difference between two different alternating currents at the same instant, or between the phase angle of the alternating voltage and the corresponding current. It might be thought that at any instant the phase angle of the current would be exactly the same as that of the voltage but, although that is true in some circuits, it is by no means always so. It is possible, for example, to have the state of affairs represented in Fig. 11 where the full line represents the variation in voltage the dotted line the corresponding variation in current. It will be noted that when the voltage has a maximum value the value of the current is zero. In this case, there is a phase difference of 90° the current lagging behind the voltage by that amount.

Such a phase difference actually exists when we are dealing with an inductance of negligible resistance. If the resistance R cannot be neglected the phase difference between current and voltage (for an inductive resistance) is

given by the angle CAB in Fig. 7. Calling this angle α , we see at once that its value may be found from the simple relation

$$\cos \alpha = \frac{AB}{AC} = \frac{\text{resistance}}{\text{impedance}}$$

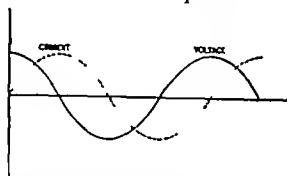


FIG. 11 Graphs showing voltage 90° in phase ahead of current.

Thus, in the example worked out on page 9 we find the amount the current lags behind the voltage by evaluating α where

$$\cos \alpha = \frac{50}{123.6}$$

Hence, phase angle $= 66^\circ 8'$

In a noninductive circuit, such as one containing an ordinary incandescent lamp the reactance is negligible, the current and the voltage are in exact step, and there is no difference in phase.

12. Power Factor — When alternating current flows in a circuit, at any instant, the power in watts = current in amperes \times potential difference in volts. The practical problem, however is to find the average value of this product over a complete cycle. When this is done, we get the expression

actual power = $VI \cos \alpha$ where

V = voltage recorded by A.C. voltmeter,

I = current recorded by A.C. ammeter,

and α = phase difference between current and voltage.

The following three different cases should be noted

(a) A noninductive circuit.

Here $\alpha = 0^\circ$ or the current and the voltage are in step, and the power = VI watts, as in D.C.

(b) An inductance of very small resistance

In this case α is very nearly equal to 90° , $\cos \alpha = 0$ and the power = 0 which means that actually there is no power loss in a reactance such as a

choke coil if the resistance is sufficiently low. This apparently strange result means that the energy stored in the surrounding medium (the magnetic field) in one part of the cycle, returns to the circuit in another. A circuit or portion of a circuit to which this applies is said to be *wattless*. It is for this reason that a choke coil is a more efficient way of changing the strength of an alternating current than an ordinary rheostat in which the power is dissipated as heat.

In a practical choke coil some such device as changing the position of an iron core, enables the operator to alter gradually the magnitude of the inductance and so gradually to vary the current.

(c) An inductive resistance, such as an ordinary electromagnet or the primary of a transformer

As an illustration consider an electromagnet, of resistance 50 ohms and inductance 0.3 henry attached to a supply voltage of 110 A.C. As we have already seen on pages 9 and 14 the impedance is 123.6 ohms, the current 0.89 amperes, and the phase difference between current and voltage $66^{\circ}8'$. Hence, the power dissipated in the electromagnet

$$\begin{aligned} &= 110 \times 0.89 \times \cos 66^{\circ}8' \\ &= 110 \times 0.89 \times 0.4045 \quad \text{“ “} \\ &= 39.6 \text{ watts.} \end{aligned}$$

The value of $\cos \alpha$ (in this example about 0.4) is called the *power factor*. It will be seen that unless its magnitude is known we cannot find the actual power consumed by an inductive circuit.

The student will realize that instead of using the phase angle, the power factor can be found at once from the ratio $\frac{\text{resistance}}{\text{impedance}}$, or in the above example,

it is equal to $\frac{50}{123.6}$

13 Capacity and Phase Difference. — When a circuit attached to an A.C. supply contains capacity and a noninductive resistance, there is again a phase difference between current and voltage, but this time the current is 90° *ahead* of the voltage. As far as phase difference is concerned, inductance and capacity have opposite effects. Therefore, in a circuit containing both inductance and capacity by suitably choosing their relative values, the lag due to inductance may be counteracted, or the net phase difference between current and voltage may be made very small. This is of importance when it is desired to reduce power loss. If a given amount of power — so many watts — is to be supplied a circuit at fixed voltage, evidently the smaller the power factor the greater the current necessary. This means a heavier demand on the carrying capacity of the wires and a bigger heat or *I²R* loss.

CHAPTER II

PRODUCTION OF HIGH VOLTAGE. PART I. THE INDUCTION COIL AND THE TRANSFORMER

To operate any type of x ray tube, a voltage very much in excess of those encountered in ordinary circuits must be available. Actual values range from less than 10,000 to more than 1,000 000 volts. In this chapter our attention is confined to means of obtaining potential differences which do not exceed 200 000 or 250 000 volts.

14 The Induction Coil. — In the early days of x rays the induction coil was the apparatus used for developing the voltage necessary to operate an x ray tube. Although the coil is practically obsolete in modern roentgenology it still has its uses, in the physiology laboratory for example, and the student is well advised to recall its main features. The basic principle is that of electromagnetic induction. A *direct* current flowing in a primary coil wrapped about an iron core is regularly made and interrupted, and, in consequence, an induced E.M.F. is developed in a secondary coil wrapped about the primary. On "make" of the primary circuit, when

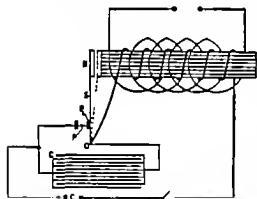


FIG. 12. Primary and secondary circuits of an induction coil with hammer break.

the lines of force are introduced this E.M.F. is in one direction; on "break," when the lines disappear in the opposite direction.

To make and break the primary circuit, an *interrupter* is used. At one time three different types, the hammer the mercury and the electrolytic were in general use, the last two being suitable when heavy power loads were needed. As the transformer has entirely superseded the coil where heavy loads are concerned, in this text reference is made only to the hammer interrupter. Figure 12 shows the essential features. When the switch *K* is closed, a direct current flows in the primary coil provided the contact points *P* and *P*₁ are touching. One of these contacts *P* is at the end of a screw passing through the rigid support *D*. The other *P*₁ is attached to the metal spring *S* which in its turn is rigidly fastened at the end *O* but is free to vibrate at the other end. At this

end it is loaded with the piece of soft iron H . Normally when no current is flowing P and P_1 are in contact. Hence, on closing the switch K the circuit is completed a current flows, the iron core is magnetized, the hammer H is attracted the spring moves to the dotted position the contact points P and P_1 are separated, and the circuit broken. The primary current then drops to zero the core loses its magnetism and the hammer is pulled back to its initial position by the elasticity of the spring S aided by an additional spring not shown in the diagram. The action which so far is essentially the same as that of an electric bell is then repeated, the primary circuit being automatically made and broken with a resulting induced E.M.F. in the secondary in one direction on make in the opposite on break.

By using a large number of turns in the secondary very high E.M.F. may be induced, provided the magnetic lines are introduced or removed quickly

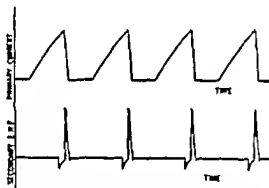


FIG. 13. Graphical representation of primary current and of secondary voltage in simple induction coil.

enough that is, provided the time of make or of break is short enough. Actually in a good induction coil the time of break is so much less than that of make that the E.M.F. induced in the secondary on break is *enormously greater* than that on make. In a small coil used by the students in one of the writer's classes, on a single break of the primary it is possible to obtain a spark between the secondary terminals of about one centimeter whereas on make the E.M.F. is so small that no spark at all can be detected. The explanation for this difference depends on more than one factor. To begin with because of the E.M.F. of inductance in the primary coil itself (see section 6) there is a delay in the rise of the current to its maximum value and the time of make is prolonged. For the same reason on break, unless special precautions are taken the E.M.F. of inductance causes marked sparking at the contact points (where the break occurs) sparking which may be followed by vaporization of the metallic terminals and resultant arcing. To suppress this sparking and arcing which prolongs the time of break a condenser C is placed across the contact points. This

CHAPTER II

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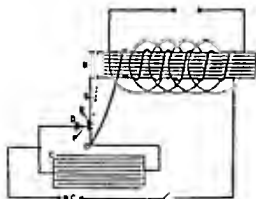


FIG. 12. Primary and secondary circuits of an induction coil with hammer break.

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secondary is greater (or less) than the number in the primary. To understand why this is so it is necessary to realize that there is an induced E.M.F. (the E.M.F. of inductance discussed in section 6) in the primary coil itself and that, when the secondary circuit is open so that no power is taken from the transformer the only function of the primary current is to maintain the alternating magnetic field. Only a small current is necessary for this. If the primary resistance is small, the actual voltage necessary to maintain the current is very small also and therefore the E.M.F. of inductance is almost equal to the

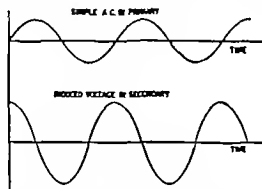


FIG. 15 Graphical representation of current in primary of a transformer and of corresponding induced voltage in secondary

applied voltage just as when a direct current motor is running freely without any external load, the back E.M.F. in the armature is almost equal to the applied voltage. Now since the same lines of force cut each turn of both primary and secondary the induced E.M.F. per turn in the secondary must be equal to the induced E.M.F. per turn in the primary. Hence,

$$\text{resultant secondary E.M.F.} = \text{E.M.F. of inductance in primary} \\ \times \frac{\text{number of turns in secondary}}{\text{number of turns in primary}}$$

Therefore, since applied voltage across primary is nearly = E.M.F. of inductance we may write with little error

$$\text{E.M.F. in secondary} = \text{primary voltage} \times \frac{\text{number of turns in secondary}}{\text{number of turns in primary}}$$

Thus, if 110 volts are applied to the primary of a transformer for which the ratio of secondary to primary turns is 1000 the secondary E.M.F. is about 110 000 volts.

The secondary E.M.F. may be either higher or lower than the primary voltage. In a *step-down* transformer such as is used for heating the filament of an x ray tube (section 56) or a rectifying valve (section 55) the voltage is

condenser prolongs still further the time of make, because on make a certain quantity of electricity flows into it. On break, the induced E.M.F. causes a further charging of the condenser and the current is not prolonged by bad sparking and arcing. If the mechanical device pulls the points apart quickly, then a very rapid break is made with a corresponding high E.M.F. in the secondary. In a good coil this E.M.F. as already noted, is so much greater than that induced on make, that the secondary terminals may be marked, one positive, the other negative, as if the coil developed a unidirectional high voltage. In a poor coil, this is far from being so.

In Fig. 13, the graphs give a general idea of the behavior of the primary current and the corresponding E.M.F. induced in the secondary.

The name *faradic* is sometimes given to induction coil currents. It will be seen that they are characterized by abrupt changes, markedly different from the smooth gradual changes of sinusoidal currents (see section 188).

15 The Transformer — For voltages up to about a quarter of a million the common device used in x ray outfits is the transformer. Here again the principle is that of electromagnetic induction. In Fig. 14, *ABCD* represents a series of sheets of soft iron put together to form a core of the shape illustrated. A coil of wire *P*, the primary, connected to an alternating source of potential difference, is wrapped about one arm of the iron core while a second coil *S*,

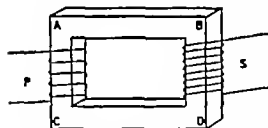


FIG. 14. Primary and secondary of a simple closed core transformer

the secondary is wrapped about an other part (or overlapping the primary). When the primary circuit is closed, the resulting magnetic field is continuously changing the number of lines rising to a maximum in one direction then decreasing to zero then increasing in the opposite direction. Whenever the number of link

ages is increasing * there is an induced E.M.F. in the secondary in one direction but when the number is decreasing (or increasing with the lines reversed) the E.M.F. is in the opposite direction. The induced voltage in the secondary therefore is alternating and of the same frequency as that of the primary current, the relation between the two being somewhat as shown in Fig. 15.

The magnitude of the secondary E.M.F. is approximately as many times greater (or less) than the primary voltage as the total number of turns in the

* An increase of lines in one direction has the same effect as a decrease of lines in the opposite direction.

rather than technical details, exact methods of constructing transformers will not be described

In ordinary problems it is usual to assume that the transformer is 100% efficient. The following example may be useful

In a step-up transformer the secondary has 1000 times as many turns as the primary. If 10 milliamperes are delivered at 100 000 volts find (i) the primary current (ii) the primary voltage

Since the secondary E M F is 100 000 volts, and the ratio of the number of turns in secondary to that in primary is 1000

$$\text{primary voltage} = \frac{100\,000}{1000} = 100 \text{ volts.}$$

If the transformer is 100% efficient, then primary voltage \times primary current = secondary voltage \times secondary current, or

$$100 \times I_p = 100\,000 \times .010$$

$$\text{or} \quad I_p = 10 \text{ amperes.}$$

Or alternately we may find the primary current at once, from the fact that, if the secondary voltage is 1000 times greater than that applied to the primary the secondary current must be 1000 times less. Hence,

$$\begin{aligned} \text{primary current} &= 0.010 \times 1000 \\ &= 10 \text{ amperes.} \end{aligned}$$

18 Transformer Rating — When a radiologist buys an x ray transformer he is interested in knowing not only what maximum voltage a machine is able to develop but also what current it will deliver at this or lower voltages. Bearing this in mind at least one firm* has adopted a standard means of specifying under three conditions of usage the peak voltage† (not the R.M.S. value) and the corresponding current as read on the milliammeter placed in the secondary circuit (see section 20). The three conditions are (a) continuous use of the transformer (b) use for a "short" period that is, for a time not exceeding 30 seconds, with rest intervals five times as long and (c) momentary use, that is, for a time not exceeding 1 second with a rest period of at least a minute in between. For example a certain transformer is advertised as having an output of 120 000 volts, peak, at 25 ma. for continuous use; or 110 000 volts at 60 ma. for a short time, or 100 000 volts at 100 ma., for momentary use.

* Watson & Sons (Electro-Medical) Ltd., London, England

† In many branches of x ray work, as will be seen later the peak voltage is more important than the average value.

lowered. In *step-up* transformers, the secondary voltage is greater, and as we have already seen, may reach or exceed 250,000 volts.

16 Insulation.—As the high tension voltage becomes greater, the problem of good insulation becomes more difficult. Injurious sparking may occur between different parts of the secondary or between the secondary and its surroundings. At one time some x ray transformers were impregnated with wax, but this method proved unsatisfactory even for only moderately high voltages. Air bubbles developed and sparking took place through the cavities thus formed. Good high tension transformers are now immersed in oil, a method which not only provides better insulation but has the further advantage that because of convection currents heat is dispersed more rapidly.

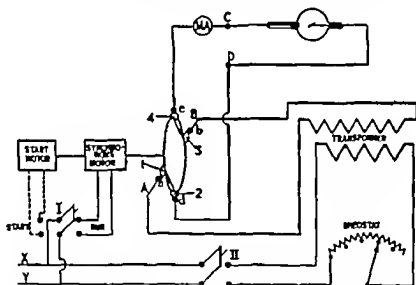
17 Efficiency and Power Rating of Transformers.—When the secondary circuit is closed, a current flows and power is delivered to this circuit. Automatically* more power is delivered by the supply source to the primary. The transformer therefore may be looked on as a mechanism for receiving power at one voltage and current and delivering it at a different voltage and current. Inevitably there is some loss in the transaction although a good transformer may have an efficiency greater than 95 per cent. The energy losses may be grouped under two headings: (a) iron losses (b) copper losses. Under (a) we include (i) the loss due to hysteresis, arising from the magnetizing and demagnetizing of the iron core and (ii) the loss due to eddy currents in the mass of the metal. The former loss is reduced by choosing a type of iron in which the magnetism lags behind the magnetizing field as little as possible; and the latter loss by the use of laminated cores.

Copper loss is the name given to the heat loss arising from the resistance of the wire carrying the current. The magnitude of this is equal to I^2R watts, where I is the customary symbol for the current in amperes, and R the resistance in ohms.

Even when all these losses are kept to a minimum high efficiency is not obtained unless the primary and secondary coils are more closely coupled than they are in Fig. 14. Good coupling is obtained by winding the primary and the secondary close together but as the aim of this text is to explain principles

* The complete explanation of the reason for this is not simple, but a general idea may be had from the following. By Lenz's law any induced current opposes the movement of the magnetic lines which cause it. Therefore the secondary current will oppose the changing magnetic flux. If lines are on the increase it will create a counterfield opposing the increase. This reduction in flux will lessen the opposing E.M.F. of induction in the primary and hence the primary current will automatically increase.

a current will flow from *A* to *a* to 1 to 2 to *d* through the bulb in direction *X* to *Y* back to *c* to 4 to 3 to *b* to the other lead wire *B*. Suppose further that during the time of one half a cycle, the disc revolves to the position shown in Fig 17. In that case since the voltage between *A* and *B* is now once more a maximum but with *A*— and *B*+, a simple inspection of the diagram in Fig 17 will show that the current flows from *B* to *b* to 2 to 1 through the bulb in the same direction as before, to 3 to 4 to *a* to *A*. In other words, if the disc can be rotated at this very exact speed then the current through the bulb will always be unidirectional. In the secondary coil of the transformer, of course it is alternating just as before. This exact co-relation between the speed of the rectifying disc and the frequency of the alternating current is obtained by means of what is called a *synchronous motor*. This is an A.C. motor which runs at a single speed only because its armature changes



[FIG. 18. Simplified connections of a transformer high tension circuit, with mechanical rectifier]

its position in exact synchronism with the changes of the current. An x ray transformer outfit with mechanical rectifier must include such a motor solely for the purpose of keeping the rectifying disc revolving at the critical speed. Moreover since the synchronous motor runs at one speed only frequently a second (starting) motor is necessary in order to bring the synchronous motor up to the desired speed. Sometimes the use of a second motor is avoided by having a synchronous motor constructed with an additional circuit which by means of a special starting switch, is put in use for a few seconds and enables the machine to run as a different kind of motor until the critical speed is reached.

19 Rectification. — For the satisfactory use of an x ray tube the voltage applied to it must be unidirectional. It may be intermittent, but unless its direction is always the same (and correct) the effect on the tube may be disastrous. As a rule, therefore, since the high tension transformer develops an alternating E M F some *rectifying* device is needed so that the voltage applied to the tube is always in the same direction. Rectification of this kind

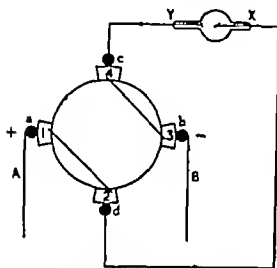


FIG. 16. Rectifying disc. Wires *A* and *B* are joined to secondary of transformer

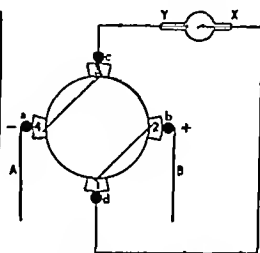
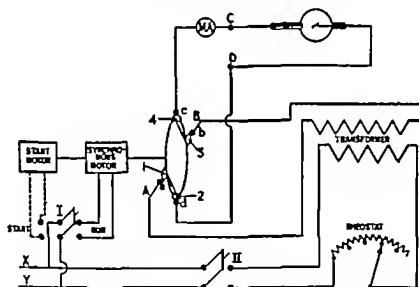


FIG. 17. Position of rectifying disc one half-cycle after that of Fig. 16.

is done either by a *mechanical rectifier* or a *rectifying valve* using a heated filament. Although the latter method has almost superseded the former an explanation of its use must be postponed until the important principle of thermionic emission has been discussed (in section 54)

The principle of the mechanical rectifier should be clear from a consideration of Figs. 16 and 17. In these figures *A* and *B* represent heavy lead wire coming directly from the high voltage side of a transformer. Each circle represents a disc which may be rapidly rotated and is made of some good insulating material. Attached to the disc are four projecting pieces of metal (1 2 3 4) 1 and 2 being connected by a piece of wire or strip of metal similarly 3 and 4. As the disc revolves, these pieces touch fixed metal brushes (*a b c d*) *a* and *b* being attached to the lead wire *A* and *B* while by means of *c* and *d*, connection may be made with a circuit containing an x-ray tube. Suppose, now that as the disc rotates, it reaches the position indicated in Fig. 16 at the moment the voltage between *A* and *B* is a maximum (the "peak" of the sinusoidal curve) *A* being $+$ *B* $-$. At that instant, then

a current will flow from A to a to 1 to 2 to d through the bulb in direction X to Y back to c to 4 to 3 to b to the other lead wire B . Suppose further that during the time of one half a cycle the disc revolves to the position shown in Fig 17. In that case since the voltage between A and B is now once more a maximum but with $A-$ and $B+$ a simple inspection of the diagram in Fig 17 will show that the current flows from B to b to 2 to 1 through the bulb in the same direction as before, to 3 to 4 to a to A . In other words, *if the disc can be rotated at this very exact speed* then the current through the bulb will always be unidirectional. In the secondary coil of the transformer, of course it is alternating just as before. This exact co-relation between the speed of the rectifying disc and the frequency of the alternating current is obtained by means of what is called a *synchronous motor*. This is an A.C. motor which runs at a single speed only because its armature changes



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20 Operation of Transformer with Mechanical Rectifier — A complete circuit, somewhat simplified, is shown in Fig 18, where λ and γ represent supply terminals, 110 or 220 A C. The supply mains branch into two circuits, one supplying current to the synchronous motor, and controlled by switch I; the other supplying current to the primary of the high tension transformer, controlled by switch II. In addition, there is the high tension circuit, including the secondary of the transformer the x ray tube and a milliammeter MA , with the rectifying disc placed so as to send a unidirectional current through the tube. The diagram should make clear without further explanation the connections of the tube circuit. It may be stated however, that the parts of the rectifying arrangement are labeled as in Figs. 16 and 17.

To operate with such an arrangement the tube* is first placed in position and connected to the high tension terminals C and D . This circuit is then closed as illustrated in the figure. Next the synchronous motor is brought up to speed. In the arrangement we are considering this is done by throwing switch I to the side marked "start", thus utilizing the starting motor, until the requisite speed is attained. Switch I is then thrown to side marked "run" and left there. The rectifying disc is now running at the necessary exact speed and may be left so for some length of time. In another machine, as already noted, there might be only a single motor with special starting switch closed initially for two or three seconds.

Finally switch II the so-called x ray switch, is closed, thus allowing current to flow in the primary of the transformer. The resulting high induced E.M.F. in the secondary then causes a current through the tube and milliammeter. The purpose of the rheostat is to alter the primary voltage, and hence the voltage applied to the tube, but that is a question we shall discuss in detail in the next chapter.

21 Nature of Tube Current. — With such an arrangement it should not be difficult to see that the tube current is intermittent. A glance at Fig 19 should make it clear that when the disc is in the position indicated in that diagram there is no current through the tube because neither a nor b touches a metal projection. Evidently the length of time the current is flowing will depend on the size and shape of the projecting pieces, that is, on the time they are in electrical contact with the lead wires A and B . This time interval therefore, may be and probably is different in different machines. If it is very short, only the "peaks" of the voltage values will be utilized as

* In a modern x ray tube an additional circuit for heating the tube filament is necessary (Chapter VI). This, however, does not alter the principle of the general arrangement explained at this stage.

represented graphically by the short heavy line in Fig 20. If the time interval is a little longer a greater portion of the whole range of voltage values will be utilized, the short heavy lines extending to the dotted parts. It is well to note further that, in order to utilize the peak voltage the disc must be in proper alignment, that is, when it is in the position represented by Fig 16 the voltage across *A* and *B* must be at its maximum value. Sometimes the disc slips on its rotating axis and gets out of alignment. To readjust it the services of an electrical engineer may be necessary.

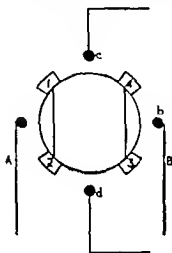


FIG. 19 Position of rectifying disc when no current is passing

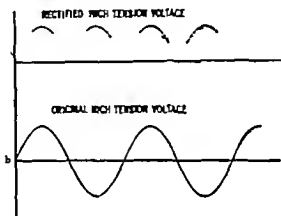


FIG. 20 Graphs to show intermittent nature of voltage applied to a tube, when a rectifying disc is used.

22. Polarity Indicator — Not only must the current through an x ray tube be unidirectional but it must be in the right direction. Now if one went through the series of operations which have just been outlined, it might be found on closing switch II that the voltage was applied to the tube in the wrong way. Just how one would know that will be explained later. In fact, if one began one hundred times at the beginning with all switches open it would be found on closing the x ray switch II that on the average fifty times the voltage was right fifty times wrong. In other words, with the above procedure, it is just an even chance whether the voltage is right or wrong. A glance at Fig 16 will explain the reason for this. In this figure it has been assumed that when the disc is in the position indicated, *A* is positive and *B* negative. Now when it is brought up to speed, there is just as good a chance of *A* being negative and *B* positive as vice versa. With the above simplified arrangement, therefore when the x ray switch is closed, one would never know whether the voltage applied to the tube would be in the right or the

wrong direction. If it were wrong it would then be necessary to open the motor switch and close it again until the right direction was obtained. This can be avoided by the use of a *polarity indicator*, a small instrument found on the control board of mechanical rectifier x ray outfits. It is essentially a direct current meter, with a pointer which moves to the left for current in one direction, to the right for current in the opposite direction. The indicator is placed in a branch circuit taken off the motor circuit, and when the motor switch is closed, a current rectified by a commutator device on the motor shaft flows through it. Depending on which way the current has been rectified, the pointer moves to one side or to the other. By a single observation the operator can find out which side corresponds to correct polarity for the tube, and ever afterwards by looking at his indicator he knows, *without closing the x-ray switch* whether the rectified voltage is correct or not. If on starting the motor the pointer on the polarity indicator is in the wrong direction by throwing over a reversing switch in the primary circuit, the operator makes sure without stopping and restarting the motor, that the secondary voltage will be in the right direction.

As already noted, mechanical rectifiers are now largely replaced by hot filament valves, which as we shall see later, require no motors and revolving discs, with their attendant noise. A full discussion of valve rectifiers and associated high tension circuits, with and without condensers, is given in Chapter VII.

CHAPTER III

MEASUREMENTS AND CONTROL OF HIGH TENSION VOLTAGE

In operating roentgen tubes it is highly important not only to be able to vary the voltage applied to the tube but also to know its actual magnitude. In this chapter important methods of doing these things are discussed. Reference is first made to several methods of measuring high voltages.

23 Spark gap Meter — The principle of this method is extremely simple — the greater the potential difference between two conductors, the longer the spark between them when the air insulation breaks down. Spark lengths may thus be equated to corresponding voltages, but in doing so one or two precautions must be considered. To begin with, the spark length depends on the shape and size of the conductors, as well as the potential difference between them. The same voltage gives a different length between two pointed than between two spherical conductors, and still different if one conductor is a sharp point, the other a plane. The length even varies for spherical conductors of different diameters, as will be seen by a glance at Table II (taken from Kaye and Laby's Tables) *

It will be noted that the lengths given in this table are for air at 25°C and 760 mm. pressure. For different values of both temperature and pressure, a correction must be made because these factors also affect the spark length for a given voltage. Table III for example gives the correction which must be applied to the values given in Table II for a few other temperatures and pressures. To illustrate, with spheres of diameter 10 cm., at a pressure = 740 mm., and temperature = 20 C., the voltage corresponding to a spark length of 2.02 cm., is not 60 000 but $60\,000 \times 0.99$.

To some extent the spark-over voltage depends also on the humidity of the air and for highly accurate work correction has to be made for this factor. A. B. Lewis has recently (1939) shown that, for voltages of the order of 10 000 there is an increase in spark-over voltage, for a fixed gap amounting to 0.13 per cent for each millimeter of vapor pressure of water in the atmosphere.

* "Physical and Chemical Constants and Some Mathematical Functions," by G. W. C. Kaye and T. H. Laby. Longmans, Green and Co.

TABLE II — (SPARKING VOLTAGES AT 25° C. AND 760 MM PRESSURE)

Kilo Volts (Peak)	Needle Points No. 00 New Sewing Needles		Spheres		
			Diameter 5 cms.	Diameter 10 cms.	Diameter 25 cms.
	cms. gap.	inches gap.	cms. gap.	cms. gap.	cms. gap.
10			0 29	0 30	0 32
15	1 30	0 51	0 44	0 46	0 48
20	1 75	0 69	0 60	0 62	0 64
25	2 20	0 87	0 77	0 78	0 81
30	2 69	1 06	0 94	0 95	0 98
35	3 20	1 26	1 12	1 12	1 15
40	3 81	1 50	1 30	1 29	1 32
45	4 49	1 77	1 50	1 47	1 49
50	5 20	2 05	1 71	1 65	1 66
60	6 81	2 68	2 17	2 02	2 01
70	8 81	3 47	2 68	2 42	2 37
80			3 26	2 84	2 74
90			3 94	3 28	3 11
100			4 77	3 75	3 49
110			5 79	4 25	3 88
120				4 78	4 28
130				5 35	4 69
140				5 97	5 10
150				6 64	5 52
160				7 37	5 95
170				8 16	6 39
180				9 03	6 84
190				10 0	7 30
200				11 0	7 76
210					8 24
220					8 73
230					9 24
240					9 76
250					10 3

TABLE III

Temp.	Pressure, 720 mm.	Pressure, 740 mm.	Pressure, 760 mm.	Pressure, 780 mm.
0°	1 04	1 06	1 09	1 12
10	1 00	1 02	1 05	1 08
20	0 96	0 99	1 02	1 04
30	0 93	0 96	0 98	1 01

In actual use a spark gap meter with spheres of a standard size is placed across the terminals of the tube as shown in Fig 21. With the tube running the distance between the gap terminals is gradually lessened until a spark takes place. To protect the surfaces of the spheres from injury due to excessive sparking series resistances RR of many thousand ohms should be placed as illustrated. It is important to note that a current should actually be flowing through the tube when the reading is taken. If no current is in the tube circuit the length of the spark measures the E.M.F. or maximum voltage got up by the transformer. When a current is flowing the voltage across the tube is less, sometimes very much less, than this E.M.F. because of the drop in potential in the secondary coil. (See also section 25.)

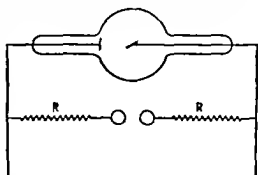


FIG 21 Sphere gap with protecting resistors, for measurement of voltage across an x-ray tube.

24 Corona. — Before leaving the subject of sparking potentials, attention is directed to the difference between a spark and *corona* or *brush* discharge. In the case of a spark the electric field between two conductors (one of which may be the earth) becomes so intense that the air resistance breaks down along what is practically a continuous path between them. A discharge passes, accompanied by a crackling sound and marked luminosity. If a conductor is at high potential the air in its immediate vicinity may become conducting without a complete breakdown between it and another conductor. In this case, a feeble discharge takes place accompanied by a glow called the *corona*, which can be seen in a darkened room. The smaller the dimensions of the conductor the more the likelihood of a corona discharge. In the early days of roentgenology the high tension leads running to the x ray tube were frequently narrow wires which were wound on a small reel. With these marked corona was a common experience. Corona is undesirable because it means not only a loss of energy but also the danger of the formation of undesirable ozone and oxides of nitrogen. It can be avoided, as it now invariably is, by the use of conductors of large size, kept well apart and well away from the earth.

25 Primary Voltmeter — The most common and certainly the most convenient, if not the most accurate method of measuring the potential difference across the terminals of a tube consists in the use of an ordinary A.C. voltmeter across the primary terminals of the transformer. The higher the

primary voltage, the greater the E M F in the secondary and the greater the voltage across the tube. Hence in any given outfit, the scale of the voltmeter may be marked to read tube voltage instead of the primary voltage which it really records. Unfortunately the scale can be exact for only one value of the tube current. It is true that for each primary voltage, there is a corresponding E M F induced in the secondary but, as we have already noted when a current is flowing in the tube circuit, the potential difference across the tube terminals is less than the E M F because of the voltage drop in the secondary winding. Now this voltage drop depends on the current, being greater the greater the current, hence for the same primary reading of the voltmeter the potential difference across the tube will decrease as the tube current increases. For example in a certain x ray transformer for a primary voltage of 80, a spark gap meter across a tube gave a reading of 3.06 inches for a tube current of 10 ma. but only 2.85 inches for a current of 30 ma.; or for a primary reading of 100 volts, the spark length was 4.51 inches for 10 ma. but only 4.10 inches for 30 ma.

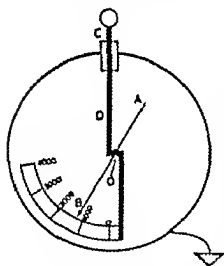


FIG. 22. The Braun electrostatic voltmeter

For very exact work, therefore, it would be necessary to have a separate scale on the primary voltmeter for each tube current. If the tube is to be used with only a narrow range of currents, this is not necessary; and, in any case a primary voltmeter calibrated to read tube kilovolts for a single milli-ampereage is an extremely useful feature of an x-ray transformer outfit. Frequently all that an operator wishes is to operate his tube at the same voltage as used previously with the same tube current.

26. Electrostatic Voltmeter — An ordinary "gold leaf" electroscope is an electrostatic voltmeter the deflection of the leaf measuring the potential difference between the charged system and the surrounding earthed case. In the Braun electrostatic voltmeter this is put to practical use for measuring voltages of the order of a few thousand. In this instrument, a movable metal strip *AB* Fig 22 pivoted at *O* is in electrical contact with the insulated metal rod *CD*. The surrounding case is grounded. When *CD* is joined to a conductor charged to high potential (for example, to one knob of a Wimshurst electrostatic machine whose other knob is grounded) the movable rod is deflected an amount which is greater the higher the potential.

For higher potentials use is made of the fundamental principle that, if a potential difference of V volts exists between two charged conductors, one positive, the other negative they are attracted with a force whose magnitude depends on the distance between the conductors, and on the voltage, being directly proportional to V^2 . If, then two plates such as A and B Fig 23 are maintained at the potential difference to be measured the force of attraction between them is proportional to the magnitude of this potential difference. If one plate is fixed and the other free to move, this force may be measured * or the arrangement may be such that a pointer moves over a scale an amount which is greater the greater the force that is, the greater the potential difference to be measured.

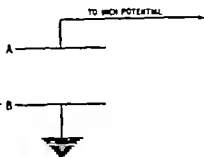


FIG. 23. If conductor A is maintained at a potential V and conductor B is joined to ground, A and B are attracted with a force which is proportional to V^2 .

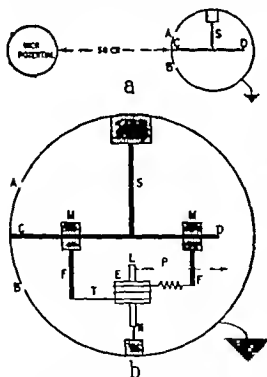


FIG. 24. An electrostatic voltmeter in which potentials of the order of 250,000 volts are measured by the movement of the sector AB .

As an illustration of an electrostatic voltmeter used for voltages of the order of a quarter of a million a brief description is given of one constructed in the Palmer Physics Laboratory at Princeton University and described in an article by C W Lampson. In this instrument the electrostatic pull is measured by the application of a simple principle in mechanics. If the bob of a simple pendulum is pulled aside by a horizontal force F the greater F the greater the horizontal displacement x . If the ball is very heavy so that it is never deflected a great deal out of the vertical the displacement x is directly proportional to the force F .

In this type of electrostatic voltmeter a sector AB Fig 24 is punched out of an 8" hollow copper sphere and then suspended so that it is

* In one standard arrangement it is weighed because the movable plate is attached to one arm of a balance.

free to move horizontally with only a small amount of clearance between the sector and the remainder of the sphere. A rod CD is rigidly attached to the sector AB and the whole hung by a suspension S *. A silk thread T is stretched between the ends of brass rods F and F' , attached to collars M and M' which are rigidly joined to the rod CD . This thread, kept under tension by a small metal spring, is wrapped around a drum E attached to the vertical cylinder LN which is pivoted between fixed supports so that it is free to rotate.

Now when the voltmeter, which is grounded, is brought in the neighborhood of a terminal charged to a potential V , as in Fig 24a, the plate AB is pulled with a force, whose magnitude as we have already noted is proportional to V^2 . The plate, therefore, and the whole system to which it is attached moves in a horizontal direction an amount proportional to this force. Because of the action of the thread wrapped about the drum the cylinder is rotated a corresponding amount, and finally the end of a pointer P attached to the cylinder moves over a scale. Thus, "the lateral motion of the sector is transmitted as rotatory motion to the pointer". The position of the pointer on the scale therefore, indicates the magnitude of the pull on the plate, that is, of the potential difference between the source of high potential and the grounded voltmeter. To read in volts the scale must be calibrated. In the instrument used at Princeton calibration was carried out by the use of a high resistance and measured current as explained in the next section; and also by absolute calculation from fundamental principles of electrostatics and mechanics.

27 Current through a High Resistance. — The student will recall that when a direct current of I amperes flows in a resistance of R ohms, the potential difference between the ends of the wire is IR volts. If, then we had a coil of 1000 ohms in a circuit and an ammeter or milliammeter indicated a current of 10 ma., we would know at once that the potential difference between the ends of the wire was 1000×0.010 or 10 volts. With a megohm or a 1 000 000 ohm resistance, a current of 10 ma. would indicate a potential difference of 10 000 volts. Given a sufficiently high resistance, therefore, it is possible to measure voltages of the order of those used in x ray work, provided a suitable instrument is available for observing the (small) current through the resistance when the high voltage is applied across it.

F D Owen King has described in the British Journal of Radiology another method of utilizing a high resistance to measure the voltage across an x ray tube when operated with constant potential outfits. This method, which it is stated, measures 250 000 volts with an accuracy of 2 per cent, consists in

* The sphere is cut into two hemispheres to enable the apparatus to be placed within it, the two parts being subsequently put together again.

measuring the voltage across a very small portion CB , Fig. 25 of the high resistance AB through which a small current flows as a result of the application of the tube voltage. The potential difference between A and B is then as many times greater than that recorded by the voltmeter attached to B and C as the resistance of AB is greater than that of CB . For the satisfactory operation of this arrangement, certain special constant "Carbo" resistances were utilized. These are "of specially prepared resistance material immersed in oil and contained in porcelain tubes, the oil serving the purpose of cooling the resistance units and preventing corona effects."

Further details concerning this method will be found in section 168

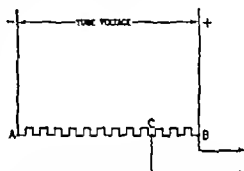


FIG. 25 By measurement of the voltage across BC a small portion of the very high resistance AB in parallel with an x-ray tube the potential difference across the tube may be measured.

28 The Seeman Spectrograph.

— This instrument provides an accurate means of measuring the maximum potential difference across a tube from observation of the spectrum of the x rays emitted by the tube. An explanation of the principle involved must be postponed until we are dealing with the nature of x rays (see section 103)

29 Control of Tube Voltage by Rheostat. — With the standard transformer arrangement, the voltage across an x ray tube may be altered and controlled by two standard means (1) the rheostat, and (2) the auto-transformer

In the rheostat use is made of the familiar IR drop in voltage due to resistance (see section 27 again). Suppose the circuit which includes the primary of the transformer is arranged as in Fig. 26. If, at the main supply terminals, the voltage is 220 A.C., then with this arrangement, the voltage across CD the primary of the high tension transformer is less than 220 by an amount which depends on the resistance of the rheostat and the current. By decreasing the amount of resistance (if the power taken from the transformer remains constant) the voltage drop in the rheostat becomes less and, therefore, the voltage across the primary greater.

In considering the rheostat method of control of voltage, one or two points should be noted.

(a) A great deal of heat is developed in a rheostat, because whenever a current flows against resistance, there is a loss in power equal to I^2R watts.

(b) Since the drop in voltage through the rheostat depends on the values of both resistance and current, a change in the current may mean a marked change in tube voltage, even for the same setting of the rheostat. For example, if the tube current is cut off without opening the primary circuit* of the transformer, the supply current in the primary circuit drops to a low value, the IR drop in the rheostat becomes much smaller, the voltage across the primary much larger, and, therefore, the E M F in the secondary much greater. This is a disadvantage, because an unduly high voltage may then be applied to the tube.

On the other hand if because of a short circuit in the tube circuit, the current supplied the primary should suddenly rise, the rheostat control has the advantage that automatically the tube voltage will drop. In this case, the

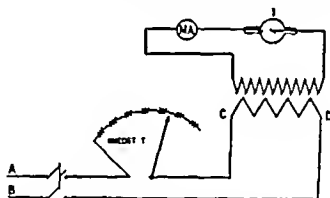


FIG. 26. Connections for simple rheostat control of high tension voltage.

sudden rise in current greatly increases the IR drop in the rheostat and so causes a corresponding decrease in voltage across the primary. The rheostat can then be considered as a kind of safety valve in the case of a short circuit.

30 Voltage Control by Auto-transformer — With the type of x ray tube now in common use, the usual method for controlling tube voltage is by means of an *auto-transformer*. This is essentially a transformer with a single winding whose ends are connected, as shown in Fig 27 to the low voltage A.C. supply mains. From B one end of the winding and C a point whose position may be varied by the use of a number of tappings, wires are led to the primary of the high tension transformer. Because of the principle

* As will be seen in Chapter VI, this can be done in hot filament tubes simply by opening the filament circuit.

of electromagnetic induction between *B* and *C* a voltage is maintained whose magnitude is in the same ratio to the supply voltage as the number of turns of the winding between *B* and *C* is to the number between *A* and *B*. By altering the position of *C* voltages ranging from zero to the full supply voltage may be applied to the primary of the high tension transformer, and so a corresponding range of voltages developed in the secondary

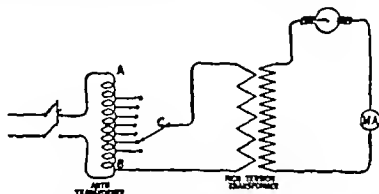


FIG. 27 Connections for auto-transformer control of high tension voltage.

Unlike the rheostat method, auto-transformer control maintains a nearly constant tube voltage even when the tube current varies, because the potential difference between *B* and *C* depends on the position of *C* and is independent of current variations in the supply mains. This has both an advantage and a disadvantage. It is certainly an advantage to have the high tension voltage remain nearly constant in spite of changing loads, because as we shall see later the nature of the x rays emitted by a tube depends on the tube voltage. On the other hand, if a short circuit develops, it is better not to have the high voltage maintained, and in this instance, rheostat control is to be preferred to auto-transformer

(a) A great deal of heat is developed in a rheostat, because whenever a current flows against resistance, there is a loss in power equal to I^2R watts.

(b) Since the drop in voltage through the rheostat depends on the values of both resistance and current, a change in the current may mean a marked change in tube voltage, even for the same setting of the rheostat. For example if the tube current is cut off without opening the primary circuit* of the transformer the supply current in the primary circuit drops to a low value, the IR drop in the rheostat becomes much smaller, the voltage across the primary much larger, and, therefore the E M F in the secondary much greater. This is a disadvantage, because an unduly high voltage may then be applied to the tube.

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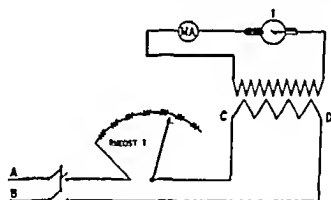


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* As will be seen in Chapter VI, this can be done in hot filament tubes simply by opening the filament circuit.

electrical machine or high voltage battery. It will now be found that, in spite of the suction through the tube, the electroscope *retains* its charge. In other words, the conducting air, after passing between the charged plates has lost its conductivity or is no longer ionized.

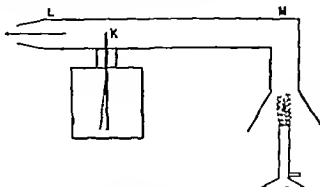


FIG. 28. Ions from the neighborhood of flame when drawn along the tube discharge the electroscope.

The removal of the conductivity by the charged plates (and many other experiments) proves that air is made a conductor because of the formation by the flame of small *electrified* particles. These particles, which we shall see presently may be either positive or negative, are called *ions*. Their existence

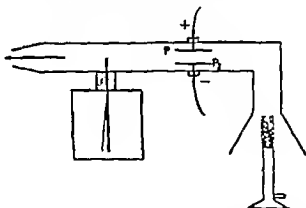


FIG. 29. Ions drawn along the tube are removed by an electric field across the plates P and P_2 .

provides a ready explanation of the discharge of the electroscope. If it is positively charged and ions are found near it, positive ions will be repelled, negative attracted. Each negative ion on reaching the insulated rod of the electroscope will annul some of the positive charge on it until finally the electroscope is completely discharged. Moreover all the time the discharge is taking place there is a stream of positive ions in one direction, negative in

CHAPTER IV

CATHODE RAYS

In the original type of x ray tube a current passes through a rarefied gas; in the hot filament tube a current passes, although the vacuum may be nearly as perfect as modern means of exhaustion can make it. Before the action of either can be understood, it is necessary to consider somewhat in detail the whole question of the passage of electricity through a gas.

31 Conductivity of Air — Suppose an electroscope made with the most perfect insulation possible is given a charge. If the deflection of the leaf is observed hour after hour it will be found that, although there is an extremely slight falling of the leaf the charge is retained even for days. We conclude, therefore, that while air is not a *perfect* insulator, at any rate it is an extremely poor conductor of electricity. (Evidence that air is not a perfect insulator has been given implicitly when it was pointed out that, once the voltage across two conductors exceeds a certain value a spark jumps the gap between them.)

It is possible however, to put air into a fairly good conducting state. A simple experiment will illustrate one means of doing so. Suppose a lighted match is held near the projecting end of a charged electroscope. It will be found that in a few seconds the leaf has fallen and the electroscope is discharged. The air in the neighborhood of the electroscope has had its conductivity enormously increased by the presence of the flame. In other words, the flame is what we call an *ionizing agent*, causing marked ionization of the air in its neighborhood.

Suppose we have an arrangement of apparatus similar to that illustrated in Fig. 28. In this case air from the neighborhood of a flame may be sucked through a tube *LM* into which projects the top *K* of the insulated rod of a charged electroscope. With such an arrangement it will be found that as soon as the air from the flame is sucked along the pipe the electroscope begins to lose its charge. Evidently air in the conducting state can be carried from place to place.

Imagine next, that the apparatus is altered so that the ionized air in its passage along the tube has to pass between two plates *P*₁ and *P*₂, Fig. 29 which are joined, one to the positive, the other to the negative terminal of an

the pressure gets lower. The harder a gas x ray tube is, therefore, the greater the voltage necessary to maintain a given current through it. Conversely the tube is said to be "soft" when the gas is in a fairly good conducting state.

33 Appearance of Vacuum Tube.—The appearance of a vacuum tube when conducting a current at low pressures is very beautiful and has certain general characteristics which it is well to note. Initially or very shortly after the gas has become conducting a single sharp narrow streamer extends the length of the tube. As the pressure is reduced the band of light becomes wider and more and more diffuse until the whole tube is filled with luminescence. At still lower pressures (of the order of half a millimeter) the tube has a striking and very characteristic appearance. (1) Around the cathode is a thin luminous layer *A* in Fig. 31. (2) next is a sharply defined dark space *B* followed by (3) another luminous region *C*, then (4) a second ill-defined dark region *D* and finally (5) a column of luminescence *E* extending to the anode. At certain pressures this column is broken up into beautiful striations, that is, narrow regions alternately dark and light.

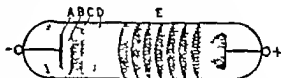


FIG. 31 Appearance of a vacuum tube carrying a discharge at a pressure in the neighborhood of one-half a millimeter of mercury.

Most important of these regions is the sharply defined dark space, the Crookes dark space as it is called, or sometimes the dark space. With decreasing pressure, its width continues to increase, and is indeed a rough measure of the degree to which the tube has been exhausted. In the case of a gas x ray tube, the dark space should fill the whole tube. If by any chance an x-ray tube presents the above appearance that is, one with marked luminescence the pressure is much too high and the tube must be re-exhausted before it is of any use. In the case of a hot filament tube careless manipulation may result in the liberation of gas. If sufficient gas is present, this will be evident by the general luminescence filling the tube when a high voltage is applied. Again re-exhaustion is the only remedy.

34 Properties of Cathode Rays.—When exhaustion is extended beyond that giving rise to the above characteristic appearance, the dark space, as already noted, grows wider and wider until it finally fills practically the whole tube. This occurs when the pressure has now been reduced* to about 1/100 mm a value which is of the order of that in a gas x ray tube. At

* We speak of raising the vacuum when we lower the pressure.

the opposite Such a stream of ions constitutes an electric current through the air

32. Conductivity of Air at Reduced Pressure. — Before explaining just what the nature of ions is, reference must be made to experiments relating to the conductivity of air at pressures considerably less than atmospheric. Suppose that the terminals of a "vacuum" tube with electrodes *A* and *B*, Fig 30, are joined to an induction coil and that the tube at the start contains atmospheric air, with the electrodes at such a distance apart that no spark discharge can take place. If now,

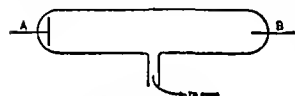


FIG. 30. A simple vacuum tube with internal electrodes.

by means of an exhaust pump, the air is gradually removed from the tube, a stage is soon reached at which a discharge passes readily, this stage being indicated by a line of luminosity which extends

from one electrode to the other. As exhaustion proceeds the current passes more and more readily until a second stage is reached beyond which the current passes less readily, until finally, when a very high vacuum has been attained, the resistance is so great that the tube will not conduct at all. Some actual measurements (taken from Townsend's *Electricity in Gases*) are given

TABLE IV

Pressure.	4 mm.	2.84	1.65	1.04	.66	.4	.29	.24	.17
Voltage	650 volts	620	500	470	490	530	590	630	740

in Table IV. This table gives the voltages necessary to maintain a current of 10 ma. through a tube 3 cm. in diameter, with electrodes 11.5 cm. apart, at various pressures.* It will easily be seen that as the pressure lowers, at first a lower and lower voltage is required, but after a certain critical value has been reached, higher and higher voltages are necessary. Evidently then, *the resistance of a vacuum tube (or a gas x-ray tube) depends on the degree to which it has been exhausted.* Moreover after a certain critical pressure has been passed, it is more and more difficult to pass a given current through an exhausted tube. Technically it is said that the tube becomes *harder* as

* Readers will recall that the pressure of a gas is frequently expressed in terms of the length of the column of mercury it will support. Atmospheric air, for example, will support a column of mercury whose height varies from day to day but is in the neighborhood of 760 mm. In the experiment to which Table IV has reference an air pressure has been reached which supports a column of mercury only 17/100 mm. high.

shadow is cast on the end of the tube all the region around the shadow strongly fluorescing. This could be caused only by a beam which, like light rays, travels in straight lines. (4) Cathode rays represent a considerable amount of kinetic energy. This may be shown by using not a plane cathode, as represented in Fig. 32 but a concave one. By this means the beam of rays (which it was pointed out above proceed normally from the cathode) can be brought to a focus at a point, as illustrated in Fig. 34. If now a thin piece of metal be placed in a tube so that the spot to which the rays are focused is on the surface of the metal, in a short time incandescence will be observed in the neighborhood of the spot. On impact of the rays against the metal a large amount of heat is developed. (This point is of very great importance in connection with the action of either the gas or the hot filament tube.) (5) Cathode rays are deflected from their path by an electric as well as by a magnetic field. To show this a tube constructed as represented in Fig. 35 is used. By having a small cylindrical opening in the center of the anode, a narrow pencil of cathode rays may be obtained. This beam may

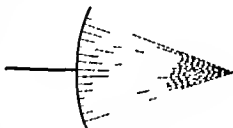
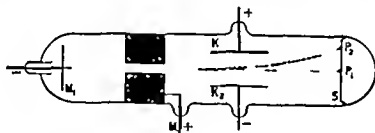


FIG. 34. Focusing of cathode rays.


 FIG. 35 Cathode rays are deflected by the electric field between the plates K_1 and K_2 .

be visible for only a short distance from the cathode if indeed it can be seen at all, but, if at the far end of the tube a fluorescent screen S be placed, the presence of the rays is at once evident by a round fluorescent spot at P_1 on the screen. Suppose now the tube has been constructed with two metal plates K_1 and K_2 and that these are joined, one to the positive, the other to the negative terminal of a battery. It will then be found that the spot of light shifts from P to P_2 . *In their passage through the electric field between the plates the rays have been deflected.*

From this and the other properties enumerated, we conclude that cathode rays consist of a stream of electrified particles. Moreover from the direction

this pressure a very faint beam of light proceeding *at right angles* to the cathode is frequently visible. Depending on conditions, this beam may be narrow, covering only a small portion of the face of the cathode, or it may cover nearly the whole of it; it may be extremely faint, or it may be well defined. (Often it is quite visible in a 'soft' x ray bulb.) The direction of this beam, moreover, is independent of the position of the anode. For example, in a tube of the shape illustrated in Fig 32 the beam is still at right angles to the cathode, although the anode is in an arm at one side of the tube.

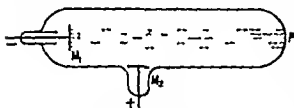


FIG. 32. Cathode rays leave the cathode normally

A second important appearance is characteristic of this stage. The walls of the tube, particularly at the end opposite the cathode, are seen to fluoresce with a glow, frequently greenish, whose color, however, depends on the composition of the glass. That the fluorescent light has some connection with the faint streamers is readily shown by simply bringing one pole of a magnet near the cathode end of the tube. Both the faint beam of light and the position of the fluorescent light at the other end move simultaneously

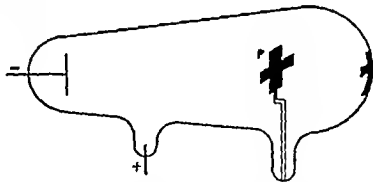


FIG. 33. A sharp shadow of the cross *P* is cast by a beam of cathode rays.

The name *cathode rays* has been given to the faint beam of light. What is their nature? Before answering this question it is desirable to look at some properties of the rays. From what has just been stated, cathode rays (1) are deflected from their path by a magnetic field and (2) excite fluorescence where they strike the walls of a glass tube. (3) They travel in straight lines when no deflecting electric or magnetic fields are present. This is readily shown by using a tube of the kind illustrated in Fig 33. With such a tube it is observed that if an obstacle *P* is placed in the path of the rays, a sharp

between two charged plates and the drops are then given a charge by ionizing the air in this region. A single drop ordinarily will fall slowly due to its weight, but, if it has a negative charge and the positive plate is above it, as in Fig. 36 the electric force acting on the drop will be in an upward direction and may easily be adjusted until it exactly balances the downward pull of the earth. The drop will then be balanced in space somewhat like Mahomet's coffin. Calculations based on this experiment enable the exact charge on the drop to be obtained and show that the charge is always equal to that on a cathode ray or to some multiple of it. Smaller amounts have never been observed, and larger amounts occur in exact multiples of this fundamental unit of charge. The actual magnitude of the fundamental or electronic unit is 4.80×10^{-10} statcoulombs,* or 1.60×10^{-19} coulombs.*

From work in electrolysis we know that 96,490 coulombs is the charge carried by the ions contained in 1.008 gm. of hydrogen, or

$$\frac{\text{charge on a hydrogen ion}}{\text{mass of a hydrogen ion}} = \frac{96490}{1.008} \text{ coulombs per gram,}$$

$$\text{or} \quad \frac{e}{M} = 9.55 \times 10^4 \text{ coulombs per gram,}$$

where e represents the charge on an hydrogen ion and M its mass.

Since experiment shows that e the charge on a cathode ray is equal to e the charge on a hydrogen ion it follows that M the mass of a hydrogen atom is about $\frac{1.76 \times 10^6}{9.55 \times 10^4}$ or about 1838 times greater than m the mass of a cathode ray †. In passing we may note that the mass of a hydrogen atom is 1.66×10^{-24} gm. that of a slow cathode ray 9.09×10^{-28} gm.

In cathode rays, then we have to deal with particles of this small mass, all carrying the same negative charge of electricity. It is important to realize that the mass of a cathode ray is the same regardless of the nature of the materials in the cathode ray tube. The cathode may be made of iron or of copper or of silver or of aluminum or any other metallic substance the gas

* It will be recalled that 1 statcoulomb is such a quantity of electricity that when placed 1 cm. away from similar quantity with air as the medium between them the force of repulsion between the charges is 1 dyne. It will be useful to remember particularly when we discuss the question of x ray dosage, that

1 coulomb or 1 ampere-second = 3×10^9 statcoulombs.

† This is true only when the speed of the cathode rays is not great. Actually the mass is a function of the velocity and at extremely high speeds the increase in mass becomes of great importance.

of the deflection by the electric field, the charge they carry is at once seen to be *negative*.

35 Nature of Cathode Rays. — The experiments which led to the discovery of these properties of cathode rays left no doubt about their corpuscular and electrical nature. Moreover they provided the answer to questions which naturally arise concerning the size of the particles, their speed, and the magnitude of the charge they carry. A glance at Fig. 35 will show that it is a simple matter to measure on the screen S the distance from P_1 to P_2 , that is, to measure the amount the beam is deflected, and it should not be difficult to see that this depends on the very things we wish to know. To begin with, the greater the electric charge the particle has and the larger the voltage across the plates K_1 and K_2 , the greater the force pushing the particle to one

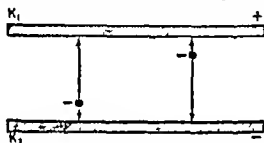


FIG. 36. The principle of Millikan's oil drop experiment. A drop, represented by the black dot, is pulled downwards by the force of gravity upwards by the electric field between the plates K_1 and K_2 .

side. But heavy particles are not pushed aside as readily as light, nor fast particles as easily as slow, hence the amount of deflection depends not only on the force acting on a particle but also on its mass and its speed. For the trained physicist comparatively simple calculations connect all these factors together, and from his calculations and observations, made with both electric and magnetic fields, it can be shown that the value of $\frac{e}{m}$, that is, the ratio of the charge carried by a cathode ray to its mass, is equal to 1.76×10^8 coulombs per gram.

As researches concerning the conduction of electricity through gases continued, it became evident that the charge carried by a cathode ray was a fundamental unit of electricity. It would be out of place in this book to refer in detail to the pioneer investigations establishing this fact, and a brief reference is made to but one outstanding investigation, the famous oil drop experiment performed by Millikan. Like a few other famous experiments it is beautiful in its simplicity. By means of an atomizer oil drops are sprayed in the space

m grams moving with velocity v cm per sec. is $\frac{1}{2}mv^2$ ergs. In the case of the cathode ray we have seen that

$$m = 9.09 \times 10^{-28} \text{ gm}$$

Therefore the kinetic energy of the particle

$$= \frac{1}{2} \times 9.09 \times 10^{-28} \times v^2 \text{ ergs.}$$

Hence,

$$\frac{1}{2} \times 9.0 \times 10^{-28} \times v^2 = 1.6 \times 10^{-8} \text{ from which}$$

$$v = 59.6 \times 10^8 \text{ cm. per second}$$

$$= 37,100 \text{ miles per second}$$

36 Structure of the Atom.—As we have just seen the discovery of cathode rays showed that atoms of all elements must contain negatively charged particles, a conclusion which was amply confirmed by subsequent work. These particles we now call *electrons* reserving the name cathode rays for electrons which are shot down evacuated tubes of the kind shown in Figs. 32 and 33. Electrons may be released from atoms in a number of different ways. A very common method which we shall discuss more fully in Chapter VI consists in heating a metal to incandescence, in which case electrons evaporate

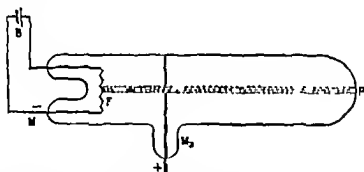


FIG. 37 A simple electron gun. Electrons are liberated from the heated filament F

from the metal, or to be more scientific, there is a *thermionic emission* of electrons. In a radio tube for example, the filament which you sometimes can see glowing, is heated to obtain a supply of electrons. If, therefore an evacuated tube is made like the one shown in Fig. 37 where the cathode of Fig. 32 is replaced by a wire* F heated to incandescence by passing an electric current through it, a beam of cathode rays is shot down the tube when the filament is joined to the negative terminal and the anode to the positive terminal of an

* Frequently the wire is coated with a material like lime or calcium oxide which liberates electrons copiously when the wire is heated at a lower temperature than is necessary for the uncoated wire.

in the tube before it was evacuated may have been ordinary air, or oxygen, or hydrogen or carbon dioxide or any other kind — in all cases the same result is obtained. All slow cathode rays have this same mass. This was a startling discovery because it proved that there was a common constituent to all kinds of matter. The atom can no longer be considered uncut or uncuttable as it was throughout most of the nineteenth century. It must contain particles with a mass nearly two thousand times less than that of the hydrogen atom.

The speed of cathode rays depends on the potential difference between the cathode and the anode in the same way as the speed of a falling body depends on the height from which it has fallen, and may be thousands of miles per second. For example for a potential difference of 10,000 volts, the speed is about 37,000 miles per second, or about one fifth of the velocity of light. For 100,000 volts, the speed is over 100,000 miles per second and for a million volts, ninety five per cent of the speed of light is obtained.

It is instructive to calculate the speed of a cathode ray for a given voltage. To do so the student must recall that unit potential difference exists between two points or two conductors, when unit amount of work is done in taking a unit charge from one point to the other or when unit amount of energy is gained if the unit charge falls under unit potential difference. To be more specific, if unit potential difference which for convenience we shall call 1 statvolt, exists between two conductors, and 1 statcoulomb falls through this potential difference the energy gained is 1 erg the fundamental unit of energy. Another important energy unit in common use is the *electron-volt*. This is the amount of energy acquired when a particle having a charge equal to the fundamental or electronic unit falls through a potential difference of 1 volt.

It follows at once that, if the potential difference is V statvolts, and the charge is e statcoulombs, the energy gained is Ve ergs. Since the usual unit of potential difference is the volt, the student should remember that 300 volts = 1 statvolt; or that to change from volts to statvolts, you must divide by 300.

Suppose, now that a cathode ray (with charge 4.80×10^{-10} statcoulombs) falls through 10 000 volts. The energy* it acquires

$$\begin{aligned} &= \frac{10,000}{300} \times 4.8 \times 10^{-10} \text{ ergs,} \\ &= 1.6 \times 10^{-6} \text{ ergs.}^* \end{aligned}$$

This energy appears as kinetic. Now the kinetic energy of a particle of mass

* This amount of energy is more often described as 10 000 electron-volts.

an electron completely out of the atom away from the attraction of the nucleus. When that has been done, the nucleus has one unit of positive electricity in excess of the amount necessary to neutralize the negative charge on the remaining electrons, and we have what is called a positive atom-ion or more often just a *positive ion*. Sometimes two electrons are removed from the atom and we then have a doubly charged positive ion. The atom in each case is said to be *ionized* and the means by which the electron or electrons have been removed are called ionizing agents. X rays, gamma rays from radium, and, as we have already seen, flames are examples of such agents. The electron which has been removed from an atom does not always remain in solitary state but frequently attracts to itself a neutral molecule or atom or possibly several of them, forming a negative ion.

On this view electricity is never created, but is of the very essence of matter. When an ebonite rod is rubbed on wool, little forces (which we do not understand any too well) are brought into play which cause electrons to pass from the wool to the rod. For every million electrons gained by the rod the wool loses a million. Consequently whenever the rod acquires a million units of negative electricity the wool having a million positive units unbalanced by the electrons it has lost, acquires an equal positive charge.

A battery or a dynamo is not a means of creating electricity but a device which separates positive from negative with a resulting potential difference between its terminals. When a current flows in a circuit, it is simply a movement of electrical charges, — sometimes electrons only, sometimes negative ions in one direction, positive in the opposite.

38. Ionization by Collision. — The ability to ionize a gas or a vapor through which it is passing is an important property of a rapidly moving electron. If moving quickly enough an electron may pass right through an atom leaving it unharmed; if moving very slowly the electron may not have enough energy to do any damage but over a wide range of speeds, it will remove electrons from many of the atoms which lie in its path. As we have seen, whenever an atom loses an electron it becomes a positive ion. Hence the path of a fast electron is marked by a trail of ions.* This production of ions by a moving particle is one of the commonest ways of making a gas conducting. In the next two chapters we shall study this method of ionization in greater detail.

39. Electron Bombardment. — Attention has already been directed to the fact that intense heat may be developed when electrons are suddenly stopped by a target. It is not surprising, therefore, that important effects may

* See section 117

induction coil or any other source of direct voltage. Such an arrangement constitutes the essential features of what is sometimes called an *electron gun*.

The new atom which contains electrons must have a structure far from simple. Since an atom as a whole exhibits no electrical charge it must contain enough positive electricity to neutralize the negative on the electrons. What does it look like, and where is the positive electricity? Can we form a mental picture of it? The answer to these questions has not always been the same, but for a number of years it has been possible to visualize a model atom which has been extremely fruitful in explaining and interpreting many facts. This atom consists of a positively charged center or *nucleus* accounting for almost the whole of its mass, together with a number of electrons *whose total negative charge exactly equals the positive charge on the nucleus*. So small are both nucleus and electron that if an atom were enlarged to be the size of a balloon 60 feet in diameter, the nucleus and each electron would not be much bigger than a grain of sand. On this view the atom is a miniature solar system with the electrons revolving about the nucleus much as the planets revolve about the sun.

To distinguish one atom from another two quantities must be known (1) the *atomic weight* or the number proportional to the mass of the atom (2) the *atomic number*. One or two concrete examples should make clear the meaning of atomic number. There is overwhelming evidence that in the atom of hydrogen, the lightest element, there is but one electron with its unit negative charge moving about the nucleus with an equivalent positive charge; in helium the next lightest element, there are two electrons and the nucleus has two units of positive electricity; in lithium the third lightest, there are three electrons and three positive unit charges on the nucleus; and, to give one other example, in the mercury atom, there are eighty electrons and the nucleus has eighty units of positive electricity. The atomic number is just the number of unit positive charges carried by the nucleus — which, of course, is the same thing as the number of electrons in the normal atom. Hydrogen, then, has an atomic number of 1, lithium of 2, helium of 3 and mercury of 80. In modern physics the atomic number is of even greater importance than the atomic weight because the chemical properties of an element depend on the number and arrangement of the electrons surrounding the nucleus, and this depends on the atomic number.

37 Meaning of Ionization. — Since negative electricity attracts positive, each electron is strongly attracted by the nucleus. This electrostatic attraction provides the centripetal force necessary to keep the electron in orbital motion about the nucleus. If it were not for its motion the electron would fall into the nucleus. By exerting a pull outwards, however, it is possible to remove

CHAPTER V

POSITIVE RAYS AND ISOTOPES

41 **Nature of Conductivity at Atmospheric Pressure.** — In section 31 it was pointed out that even with the most perfect insulation available, an electroscope slowly loses its charge. It should now be evident that, if a few stray ions are at all times present in ordinary air, a ready explanation of this discharge may be given. As a matter of fact, a large number of investigations, many of them dating back to the beginning of this century, have shown conclusively that there is no doubt about the presence of such ions. If then an intense electric field is created between two conductors such as the knobs of a simple electrostatic machine or the secondary terminals of an induction coil, these ions, being charged particles, are acted on by a big force and very quickly acquire a high velocity. If the field is intense enough, the ions have sufficient kinetic energy to ionize neutral atoms or molecules against which they collide. The ions and released electrons resulting from such collisions in their turn are speeded up by the electric field and very quickly they too ionize other atoms and molecules. In this way once an electric field of sufficient intensity has been reached ionization increases so rapidly that a sudden discharge made evident by the crackling spark, takes place. In the case of corona, the field is intense enough to cause a discharge only within a limited region near the high potential conductor. If an earthed conductor should be brought too near the corona will of course give way to a spark.

42. **Conductivity at Reduced Pressure.** — When even a tolerably high voltage is applied to tubes of the kind illustrated in Figs. 30, 31 and 32 no discharge passes if the contained air is at atmospheric pressure because the field between the electrodes is not sufficiently intense to enable the stray ions to acquire sufficient energy to ionize the neutral atoms or molecules with which they collide. When a partial vacuum is created, however, as we have already noted in section 32 there is a discharge in the tube. Because of the greater distance between individual molecules at the lower pressures, an ion now moves a greater distance without obstruction and so has a chance to acquire more energy before an impact takes place. A pressure is reached when the energy so acquired is sufficient to enable the ion to ionize on collision and there is a rapid accumulation of ions. A current passes, positive ions moving towards

be brought about by controlled bombardment of certain materials by electrons or cathode rays. In a recent issue of the *Review of Scientific Instruments* (March 1939) an article describes the construction of an *Electron Tube for the Production of Homogeneous Beams of Cathode Rays from one to fifteen kilovolts*. This tube was to be used for a quantitative study of the effects of electron bombardment on certain single-celled organisms. " At the time of writing the results of such a study are not available but there is no doubt that valuable information will be obtained by such experiments.

Much faster electrons have been utilized in certain bombarding experiments, in which the cathode rays, after passing right through a thin sheet of metal in the wall of the cathode ray tube emerge into the outside air. Tubes of this kind are sometimes called Lenard Coolidge in honor of Lenard, a German physicist, and Coolidge the present director of the General Electric Research Laboratory at Schenectady N. Y. Lenard in the last decade of the nineteenth century, made pioneer investigations relating to the passage of cathode rays through metallic foil. Coolidge followed up his work using potential differences exceeding a million volts to speed up the rays. Coolidge and other workers have shown that, under the action of these cathode rays outside the tube yeast, ergosterol and a few other substances produce vitamin D that new species may be originated in plants and in animals; that changes in color may be brought about in glass and other substances; and that it is possible to distinguish natural from artificial sapphire by the difference in their response to the rays.

40 **Origin of Roentgen Rays.** — For the radiologist probably the most important use of cathode rays is to generate roentgen or x rays. When cathode rays or high speed electrons are suddenly stopped by impinging against a hard metal target, the spot struck by the beam is the source of the invisible light called x rays. Details concerning tubes used for this purpose as well as concerning the properties of such tubes will be given in Chapter VI. Before doing so, it is desirable to consider further details concerning the passage of electricity through a rarefied gas.

(2) It is much more difficult to deflect canal rays, stronger electric and magnetic fields being necessary to do so. As a matter of fact, Goldstein tried unsuccessfully to deflect them with a magnetic field. The reason for the difficulty in deflecting the rays is due to the much heavier mass of an ion than that of a cathode ray because as we pointed out when dealing with the deflection of cathode rays, the heavier a particle is, the harder it is to push it out of its path.

(3) Measurements of the same kind as are used in cathode-ray deflection tubes show that canal rays are of atomic size, but that their masses are not always the same. If the gas in the discharge tube is changed the masses of the canal or positive rays are altered also. Again this is to be expected once we realize that positive rays originate in the positive ions in the discharge tube.

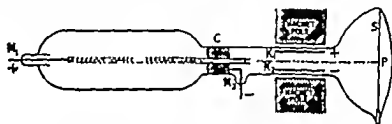


FIG. 40. A simple tube for the analysis of a beam of positive rays.

If a tube contains hydrogen then ionized atoms of hydrogen will pass through the hole or holes in the cathode; if oxygen, then oxygen atom-ions; and if there is a mixture of these two gases, in the canal ray beam there will be both oxygen and hydrogen ions.

44 **Chemical Analysis by Positive Rays.** — If a positive ray beam containing a mixture of ions of different masses passes through an electric and a magnetic field, it will be sorted out into its components. This is the principle of the positive ray method of chemical analysis which was first used by J. J. Thomson with such remarkable consequences that it is necessary to understand it clearly. In the method originally used by Thomson a tube was built somewhat as shown in Fig. 40. The rays pass through a fine tunnel in the cathode *C* and on emergence travel across a highly evacuated region until they strike a screen *S* (or a photographic plate) at the end of the tube. When the screen is coated with certain materials there is a fluorescent spot of light at the place *P* struck by the rays or if a photographic plate is used the rays affect it much as light does, and on development an image of the spot is obtained. In Fig. 41 an original photograph taken by Thomson the spot at the lower center was caused by such a narrow beam of undeflected rays.

If however the beam passes between the electrified plates *K*₁ and *K*₂, that

the cathode, negative ions and electrons towards the anode. If a stream of cathode rays is wanted, the vacuum is made so good that the liberated electrons, largely formed in the neighborhood of the cathode, move the full length of the tube with little obstruction. Figure 38 is an attempt to depict the state of affairs at somewhat higher pressures, when the tube is filled with light, as

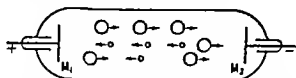


FIG. 38. In a tube containing a little gas at not too low a pressure numerous positive and negative ions move in opposite directions.

in an electric neon sign. At this stage there are numerous positive and negative ions.

43 Positive Rays.—The existence of a stream of positive ions may be shown very beautifully by using a tube in which holes are made in the cathode, not the anode, somewhat as shown in Fig 39. At suitable pressures, in *B* the portion of the tube beyond the cathode, a narrow beam of light is seen as



FIG 39 A canal ray tube. Positive ions pass through the perforations in the cathode and, at suitable pressures, give rise to colored canal ray streamers.

a continuation of each hole in the cathode, an observation made in 1886 by the German scientist Goldstein. At that date, it must be remembered, neither electrons nor ions had been discovered, and Goldstein not knowing the true nature of the rays passing through the holes in the cathode appropriately called them *canal rays*. It remained for

another German, Wien, in 1898 to show that canal rays, if made to travel through either an electric or a magnetic field, were deflected to one side, just like cathode rays, and so were electrified particles. There are three very important differences, however, between canal and cathode rays.

(1) The direction of the deflection of canal rays in a tube like the one shown in Fig 40 where a narrow beam passes between the electrified plates, K_1 and K_2 , is *towards* the negative plate, not *away* from it as in the case of cathode rays. Canal rays, therefore, must be positively charged. This, of course, is just what one should expect, for they are nothing but the stream of positive ions which come up to the cathode and pass through its perforation. In fact, J. J. Thomson, the famous English physicist who was one of the pioneer workers with these rays, changed their name to positive rays.

(2) It is much more difficult to deflect canal rays, stronger electric and magnetic fields being necessary to do so. As a matter of fact, Goldstein tried unsuccessfully to deflect them with a magnetic field. The reason for the difficulty in deflecting the rays is due to the much heavier mass of an ion than that of a cathode ray because as we pointed out when dealing with the deflection of cathode rays, the heavier a particle is, the harder it is to push it out of its path.

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FIG. 40. A simple tube for the analysis of a beam of positive rays.

If a tube contains hydrogen, then ionized atoms of hydrogen will pass through the hole or holes in the cathode; if oxygen then oxygen atom ions; and if there is a mixture of these two gases, in the canal ray beam there will be both oxygen and hydrogen ions.

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If however the beam passes between the electrified plates *K*₁ and *K*₂, that

is, through an electric field, and at the same time between the poles of a magnet, there is a sorting out of the rays or ions. When the fields are so arranged that one pushes the particles vertically, the other horizontally, then all particles of the same mass and same electric charge, regardless of their speed, strike the screen or the photographic plate along a curved line. It is much the same as if bullets of different sizes were emitted by a machine gun and on their way to a target were acted on by two forces, one pushing them sideways, the other up or down. With such an arrangement all the bullets of one size would hit the target along one line, of another size along a different line, and so on. If a positive ray beam contains singly charged atoms of hydrogen or oxygen and of nitrogen there is a curved line on the plate corresponding to each kind of atom. In Fig 41 the beam which was analyzed in this way has given rise to four or five such curved lines, the line marked 1 arising from singly charged hydrogen atoms, that marked 2 from singly charged hydrogen molecules, which have double the mass since a molecule of hydrogen contains two atoms.



Courtesy Sir J. J. Thomson,
On Royal Society and Lerner
Mass Gram and Co.

FIG 41 Positive Ray
Analysis — Early
Parabola Method,
showing hydrogen
atoms and molecules.

This method of analysis has many advantages. Only an extremely small amount of a substance is necessary to have its presence revealed in this way.

The method is even more sensitive than the spectro-

scope in detecting an element. It may reveal the existence of temporary unstable groups of atoms which change into something else after the discharge is over. Moreover on a single photograph a record is left of all the materials which take part in the discharge. A beautiful example of such a record taken by Harmsen a German scientist, with an improved form of Thomson apparatus and reproduced through the kindness of Julius Springer publisher of *Zeitschrift für Physik* is shown in Fig 42.

It will be noted that opposite each line on this photograph a number is printed. These numbers give the masses of the corresponding particles on the usual atomic weight scale and it is hoped that they will emphasize the biggest of all the advantages of positive ray analysis—the accurate comparison of atomic weights. For this purpose the relative displacements of different lines on the plate must be measured. This could be done with fair accuracy on Thomson's original curves, and, indeed, in his hands gave remarkable results, but an improvement in his apparatus was necessary for the exact measurements which modern science demands. Realizing this, Dr F W Aston, originally

a collaborator of Thomson designed new arrangements which gave greater and greater accuracy and led to results of sufficient importance to win for him a Nobel prize. During recent years his work supplemented by others, but notably by Bainbridge and by Dempster in the United States has been one of the most important lines of investigation in experimental physics.

In the forms of apparatus used by the modern experimenters the sorting out of the ions depends, as in the original arrangement, on a suitable combination

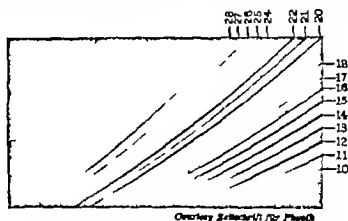


FIG. 42. Positive Ray Analysis — Later Parabola Method. Note the isotopes of neon, mass numbers 20 and 22.

of electric and magnetic deflecting fields, and the details of construction need not concern us. In the final photograph however we must note one difference. Short straight lines replace the long curves of the Thomson method. A typical photograph is shown in Fig. 43.



FIG. 43. Positive Ray Analysis — Modern Mass Spectrum, showing isotopes of cadmium.

Students familiar with photographs of optical spectra will note the similarity (See section 88). Just as a beam containing a mixture of different kinds of light on passing through a prism is spread out into a spectrum showing all its components, so the beam of positive rays by this method is separated into its constituents. It is not surprising that the apparatus used in the analysis is called a *mass spectrograph*, and the photograph, in which each line corresponds to an ion of a definite mass, a *mass spectrum*. By measuring the separation of the lines along such a spectrum an accurate comparison of masses and hence of atomic weights, may be made.

45 Isotopes — An analysis by Thomson in 1912 of the contents of a discharge tube containing small quantities of the rare gas neon, led to a very important discovery. This gas, it will be recalled, has an atomic weight of 20.2. Now on his plates Thomson obtained not only a curve corresponding to an atomic weight of 20, but also one corresponding to atomic weight 22. Although there was no known element with the latter atomic weight, the evidence suggested that neon was responsible for both lines. In 1919, Aston, who had resumed his work after the Great War, showed that there was no doubt about this conclusion. *The element neon was a mixture of two groups of atoms, one of atomic weight 20, the other of atomic weight 22, mixed in such proportions that they gave the value of 20.2 determined by chemical means.*

It will be recalled that according to Dalton's Atomic Theory the atoms of an element are identical. Here was unmistakable evidence that an ordinary element might have two kinds of atoms, of different atomic weights, but with the same chemical properties. As a matter of fact it was easy to accept this conclusion because previous investigations had shown that in unstable radioactive elements, the same phenomena occurred. In the field of radioactivity, which will be discussed in Chapter XIII scientists had become familiar with groups of two or more elements whose atoms have the same number of electrons and identical chemical properties, but different masses. Indeed, in 1913 Soddy one of the pioneer workers in radioactivity, had coined the name *isotope* to designate each member of such a group. The Thomson Aston discovery was none the less of extreme importance because it showed that isotopes could exist in ordinary, that is, nonradioactive elements.

With improved forms of mass spectrographs, it soon became evident that isotopes were the rule, not the exception as a glance at Table XXXI at the end of the book, will show. In the element tin for example whose atomic weight is usually given as 118.7 there are no less than ten isotopes, with masses ranging from 112 to 124. Although these masses are different, *the atomic number that is the number of unit positive charges on the nucleus or the number of surrounding electrons in each is exactly the same namely 50.* Since the chemical properties depend on this extra nuclear structure the isotopes cannot be separated chemically. Each isotope belongs to the element tin. It is, therefore, not the mass of an atom which tells you its name, but its atomic number. The distinguishing label of tin is its atomic number 50; of silver its atomic number 47; of sodium its atomic number 11; of mercury its atomic number 80; and so on. We may even have different elements with atoms of the same mass. For example, the metallic element calcium with atomic number 20 has an isotope of mass number 40 and so has the gaseous

element argon of atomic number 18. Elements with the same mass number but different atomic numbers are called *isobars*.

By a number of methods it is now possible to separate out usable amounts of the individual isotopes of a few elements.

46 Determination of Atomic Weights by Physical Method. —

If neon has two groups of atoms of mass numbers 20 and 22 * what, it may be asked, is the atomic weight of this element? Can this result be reconciled with the atomic weight of 20.2 determined by chemical means? In chemical reactions the groups of isotopic atoms are not separated and the atomic weight determined chemically is an average value based on combining weights. To obtain the same average value from mass spectrograph data we must know the relative amounts of each isotope. This information is readily obtained from the degree of blackening of the mass spectrum lines on the photographic plate, because the larger the number of ions which strike the plate the blacker or the denser the image. Neon photographs, for example show that the 20 component is nine times more dense than the 22. It is just a matter of simple arithmetic to show that the average atomic weight is 20.2.

47 Discovery of Deuterium. — The mass spectrograph therefore, has provided a method of obtaining atomic weights *entirely independent of the old established chemical means*. If both methods are reliable values obtained by the two methods should agree. In 1929 the agreement was remarkable, the difference between corresponding values being only about 1 part in 10 000. In that year however it was shown that oxygen which hitherto had been considered an element with only one isotope, of mass 16 had isotopes 17 and 18 present in small quantities. This meant that if the whole system of atomic weights is based on the assignment of 16.000 to the main isotope of oxygen, the average atomic weight of oxygen (the value based on all its isotopes) is slightly greater than 16.000 or conversely if the *chemical determinations* of atomic weights are continued to be given in terms of 16.000 for oxygen then the values for all other elements should be slightly less than those determined by the mass spectrograph method. The correction to be made is slight, but it was enough to indicate a disagreement between the atomic weights of hydrogen as determined by the two methods, which was just greater than possible experimental errors. Birge and Menzel, American physicists, suggested that the lack of agreement might be due to an undetected isotope of hydrogen of mass number 2. Urey, Brickwedde, and Murphy American scientists also set out to look for such an isotope spectroscopically and in 1932 announced

* The most accurate results show that there is a faint third component of mass 21

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measurements of the displacement of the isotopic lines on a mass spectrum plate may be made to a high degree of accuracy. The results of such measurements show that in all cases, masses of isotopes are *very nearly* whole numbers. The few values given in Table V will illustrate the point.

TABLE V—A FEW EXACT VALUES OF ISOTOPIC MASSES IN TERMS OF OXYGEN 16 = 16.0000

Element	Mass Number	Mass
Hydrogen	1	1.0081
Deuterium	2	2.0147
Helium	4	4.0040
Lithium	6	6.0170
Lithium	7	7.0182
Beryllium	8	8.0080
Boron	10	10.0160
Boron	11	11.0128
Carbon	12	12.004
Nitrogen	14	14.0075
Oxygen	16	16.0000
Neon	20	19.9986
Aluminum	27	26.9909
Argon	40	39.9754

With the discovery of the "nearly whole number rule" for all isotopes, it was inevitable that the hydrogen atom or more accurately its nucleus called the *proton* should be considered as an ultimate unit in the building of more complex atoms. At any rate serious attention was given the theory that the nuclei of all atoms, in some way are made of protons, with their positive charges, and negatively charged electrons. As we shall see later this view is not now held although the proton still remains as one of the fundamental particles in the formation of nuclei. Before considering further questions relating to the structure of matter it is desirable now to return to a detailed discussion of roentgen rays.

the discovery of heavy hydrogen or *deuterium* (symbol D) of mass number 2. In a tank of ordinary hydrogen there is only one part of the heavy variety to several thousands of the light, but after the original discovery of deuterium means were soon found of increasing its concentration, and eventually of completely isolating it.

Had it been just another new isotope, there would have been nothing very startling about the discovery of deuterium. As it was, it created a stir in scientific circles the world over, and in a very short time gave rise to a wealth of researches in chemical and physical laboratories. The reason is not far to seek. In so far as the positive charge on the nucleus and the number of extra-nuclear electrons are concerned, two isotopic atoms are exact twins and cannot be distinguished by any differences in properties which depend on these factors. If the ratio of the nuclear masses is nearly unity, as in chlorine with its isotopes 35 and 37, it is only by refined means that very slight differences depending on this change of mass can be detected. When however, the masses differ as much as they do in the two isotopes of hydrogen that is, in the ratio of 1 to 2, differences in their properties are easy to detect. In both physics and chemistry therefore, the discovery of heavy hydrogen was followed by hundreds of investigations, all seeking to find out differences in the properties of all sorts of compounds when ordinary hydrogen is replaced by deuterium.

Outstanding among these researches were those dealing with heavy water the compound formed when deuterium unites with oxygen to form D_2O . You cannot distinguish the two kinds of water by looking at samples of each but there are decided differences in their properties. For example, common water freezes at $32^\circ F$ and boils at $212^\circ F$., whereas the corresponding temperatures for heavy water are $38.8^\circ F$ and $214.5^\circ F$. Again the vapor pressure of H_2O at $212^\circ F$ is 760 mm Hg but that of D_2O at the same temperature is only 721.6 mm.

48. The Proton. — We have seen that the sorting out of positive rays has led to a physical method of determining atomic weights, to the discovery of the existence of isotopes in general and of heavy hydrogen in particular. Of even greater importance for the development of physics is the use of the mass spectrograph for the accurate measurement of the masses of all isotopes, in terms of the number 16 0000 assigned to the main isotope of oxygen. Hitherto we have been using whole numbers, — the so-called *mass numbers* 35 and 37 for chlorine, 1 and 2 for hydrogen 20 and 22 for neon 16 17 and 18 for oxygen — as the values of atomic masses, without any explicit reference to their exact values. Now with the improved modern instruments,

measurements of the displacement of the isotopic lines on a mass spectrum plate may be made to a high degree of accuracy. The results of such measurements show that in all cases, masses of isotopes are *very nearly* whole numbers. The few values given in Table V will illustrate the point.

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Boron	11	11.0128
Carbon	12	12.004
Nitrogen	14	14.0075
Oxygen	16	16.0000
Neon	20	19.9986
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With the discovery of the nearly whole number rule for all isotopes, it was inevitable that the hydrogen atom or more accurately its nucleus called the *proton* should be considered as an ultimate unit in the building of more complex atoms. At any rate serious attention was given the theory that the nuclei of all atoms, in some way are made of protons, with their positive charges, and negatively charged electrons. As we shall see later this view is not now held although the proton still remains as one of the fundamental particles in the formation of nuclei. Before considering further questions relating to the structure of matter it is desirable now to return to a detailed discussion of roentgen rays.

CHAPTER VI

ROENTGEN TUBES

49 Two Types of Tubes. — At the end of Chapter IV it was pointed out that x rays originate when a beam of fast moving electrons is suddenly stopped on striking a target of hard metal. To obtain a suitable beam of electrons two important methods have been used with two corresponding types of x ray tubes. In the first type, the gas tube, a residual vacuum is left at such a pressure that a well-developed beam of cathode rays is projected from the cathode, while at the same time positive ions move toward this electrode. In the second type, the hot filament tube, electrons are emitted from a heated filament which also functions as the cathode of the tube. In this type the

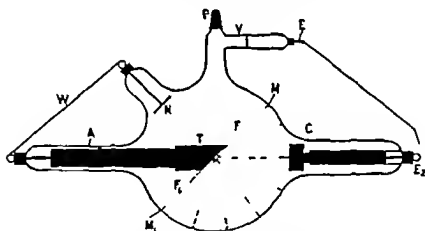


FIG. 44. A typical gas x-ray tube.

vacuum must be so good that there is no cumulative ionization by collision (section 38) or in other words, so that there is no appreciable electron flow arising from this cause.

50 The Gas Tube. — Although it would be difficult to find a modern radiology center where gas tubes are now in actual use,* a brief reference will be made to this type in order to illustrate certain basic principles. The main features are illustrated in Fig. 44 where C is the cathode, with face concave

* Special gas tubes such as one designed by Mueller are still used, particularly in connection with x ray spectrographs.

or cup-shaped so that the cathode rays are brought to a focus on the face of the target. From the *focal spot* x rays spread out in all directions, passing through the whole half of the hemisphere in front of the plane MFM_1 . Here it may be noted that when the current through a gas tube is in the right direction the portion of the bulb in front of the plane MFM_1 is usually strongly fluorescent, being separated from the remainder by a sharp line of demarcation. The target T forms the end of a long metal arm A the anticathode which by means of the connecting wire IV is in electrical contact with N the anode. The anode N lies within a short side arm of the tube, and does not project into the main body of the tube. V is another side tube which carries a third electrode E and is added for the purpose of regulating the gas pressure in the bulb. P represents a rubber tip covering the place at which the tube was sealed off from the exhaust pump after the initial exhaustion had been completed.

51 Regulation of Current in Gas Tube. — It will be seen later that the nature of the beam of x rays leaving a tube depends both on the current, that is, the milliamperage and on the voltage across its terminals. An operator therefore, must be able to control both the current and the voltage. Now if the pressure of the residual gas remains constant, the higher the voltage applied to a tube the greater the current through it. There are cases, however where an operator may wish to change to a *higher* voltage without altering the milliamperage, or possibly with even a smaller milliamperage. How can this be done? To understand the answer to that question it is necessary to remember that the voltage required to maintain a given current through an ordinary vacuum tube varies with the pressure of the contained gas. (See section 32.) If therefore, by any means the gas pressure in any x ray bulb is altered a different voltage will be required to pass the same current through it. If the vacuum is lowered (pressure increased) the resistance of the tube decreases or it becomes softer. If the vacuum is raised, the tube runs "harder" that is, the resistance increases. A soft tube, therefore is more conducting than a hard one*. Putting it in another way, a higher voltage is necessary to maintain a certain milliamperage through a tube when it is hard than when it is soft. For a given tube some regulation of the degree of vacuum may be obtained by the use of vacuum regulators. Because gas tubes are almost obsolete in x ray practice, details about such regulators are omitted, although it may not be amiss to point out that, by using the third

* Later we shall see that the terms hard and soft are also used to describe the character of the rays leaving a tube.

electrode *E*, Fig 44, to pass a momentary current through the side arm *V*, small amounts of gas may be released from material packed in this arm and the pressure increased accordingly

52. Blackening of Tubes.—With gas tubes, this slight increase in pressure is necessary, because with continued operation they are found to run harder, that is the vacuum improves. The same improvement in vacuum occurs when a gas tube has been standing idle for some time. This gradual hardening is due largely to the absorption or adsorption of some of the residual gas by the walls and the electrodes of the tube. The adsorption is increased by the presence of a black metallic deposit which gradually forms on the inner walls of the tube—a deposit somewhat similar to that which may be observed on the walls of an old 'clear glass' tungsten filament lamp. Besides increasing the rate at which the residual gas is adsorbed, the presence of blackening is objectionable, because it increases the resistance of the tube, it makes possible sparking along its walls, and it increases the danger of puncture.

TABLE VI

Metal	Atomic Weight	Atomic Number	Melting Point	Thermal Conductivity	Specific Heat	Volatilization Detectable at
Platinum	195.2	78	1750°C.	0.17	.03	1200°C.
Iridium	193.1	77	2250°C.	0.17	.03	1400°C.
Osmium	190.9	76	2700°C.	0.17	.03	2300°C.
Tungsten	184	74	3300°C.	0.35	.03	1800°C.
Tantalum	181.5	73	2900°C.	0.12	.04	
Molybdenum	96	42	2500°C.		.07	
Copper	63.6	29	1084°C.	0.92	.09	
Nickel	58.7	28	1450°C.	0.14	.10	

Blackening is the result of two causes (1) the evaporation of hot metals, and (2) a cathodic disintegration known as *sputtering*. Sputtering consists of the ejection of metallic particles from the cathode. These particles, it is to be noted, are tiny pieces of metal and must not be confused with electrons. In a good tube therefore, blackening is minimized by choosing a metal for the cathode which experiment has shown sputters a minimum amount (aluminum for example) and by keeping the metal parts, particularly the target, as cool as possible, in order to prevent vaporization. We have already pointed out that a beam of cathode rays represents a considerable amount of energy and that at the focal spot where this energy is concentrated, enough heat may be developed to make a small hole in the face of the target. More

over if the metal does not actually melt it may easily become so hot that marked vaporization takes place. Evidently it is desirable to choose for use as target a metal with a high melting point and to adopt some means of keeping it cool.

In this connection the information given in Table VI is of interest. It will be noted that platinum which in the pioneer days of roentgenology was the metal used to the greatest extent as target, is by no means the most satisfactory. Compare it with tungsten for example. Its melting point, 1750°C is little more than half that of tungsten 3300°C . Moreover platinum is one of the metals which sputters readily whereas tungsten sputters but little. For this reason should any inverse current be present in the case of a platinum target tube, blackening would soon be pronounced. (During inverse the anticathode will act as cathode.) Tungsten therefore gradually replaced platinum partly perhaps largely because of the research work of the General Electric Company Schenectady on the production of wrought tungsten.

53 Methods of Cooling a Target. — To keep the target cool use is made of several simple physical principles. In many gas tubes, the target at one time was just a "button" of tungsten set in the end of a massive piece of copper which served as a connecting conductor between the target and the external electrode. Now copper it will be noted by a glance at Table VI, has both a high thermal conductivity and a high specific heat, and hence for both reasons, the temperature rises slowly.

Additional cooling is often brought about by attaching to the end of the anticathode (or anode) outside the tube sheets of metal which because of their large surface are good radiators of heat. (See Fig 59 and Fig 65.) Cooling is also often accomplished by the use of water-cooled targets, a very efficient method because circulating water continuously carries away the heat developed. Even if the water is not renewed by inlet and outlet pipes, its temperature cannot rise above 100°C hence as long as there is water in the water cooler attached to the anode (see Fig 66 and Fig 67) high temperatures are not possible. Still another method consists in the use of an anode so massive that a large amount of heat is necessary to increase its temperature an appreciable amount. (See Fig 68.) As most of these cooling devices are employed in hot filament tubes, further reference to them will be postponed until this type of tube is under discussion.

54 Thermionic Emission. — It has already been noted that in many hot filament tubes the vacuum is nearly as perfect as modern means of exhaust-

tion can make it. So high is the vacuum that if an attempt is made to use one as a gas tube, no current passes even with a very high voltage across the tube. How, then, does it operate? To answer that question, it is necessary to explain in greater detail the subject of thermionic emission of electrons, to which a brief reference was made in section 36. This can best be done by reference to one or two simple experiments. Figure 45 represents a highly exhausted glass bulb provided with three electrodes or terminals, 3 joined to an inner sheet of metal *P* which we shall call the plate; 1 and 2 to the ends of a filament *F* of fine wire tungsten for example. Terminals 1 and 2 are connected to a storage battery by means of which current may flow through the

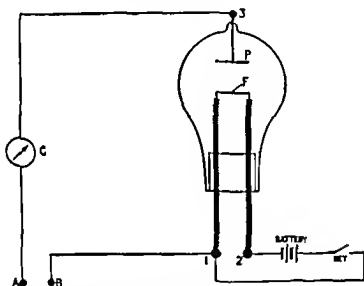


FIG. 45 A thermionic current flows across the highly evacuated tube, when the filament *F* is hot and is negative.

filament and heat it to incandescence. A second circuit including a galvanometer *G* or a milliammeter is made by joining the 110 D.C. terminals *A* and *B* to 1 and 3 as illustrated in the figure. A deflection of *G* will then indicate a current flowing around the circuit *A* to *G* to 3 to plate to filament to 1 to *B*. Is there any such current? We distinguish two cases. (1) With filament cold, that is, key open it is found that, no matter what the polarity of *A* and *B* is, no current is indicated by *G*. (2) With the filament incandescent (key closed) however if *B* is negative, a marked current is indicated whereas if *B* is positive, no current passes.

Evidently therefore, a current passes through such a tube when the filament is hot and when it is negative. Now what is the explanation? It is found in the fact that any hot piece of metal is a source of electrons. At the surface

of metals a process somewhat akin to evaporation goes on as a result of which, at high temperatures, there is a copious emission of electrons known as a *thermionic emission*. In the above tube therefore, the hot filament liberates electrons if the filament is negative, and the plate positive since negative repels and positive attracts negative electricity these electrons are driven across the vacuum space. There is, therefore a current of electricity which in this case, consists of a stream of negatively charged electrons. If the filament is positive, however because of the attraction of positive for negative the electrons cannot escape from the filament and no such current exists.

It is well to note that, although the electrons move from the filament to the positive plate, the direction of the current is from plate to filament. This is because of the convention that current direction is that in which positive electricity moves. Negative electrons coming out of a conductor is equivalent to positive electricity flowing into it.

55 Hot Filament Rectifiers. — It should now be evident that if the supply voltage is 110 *alternating* a stream of electrons will cross the tube only during the half-cycle when the filament is negative. In other words, an intermittent but unidirectional current flows in the circuit containing *G* although an alternating voltage is applied. A tube of this sort, frequently called a *diode* therefore, is an excellent rectifier and has many practical applications. For example in high tension circuits, rectifying valves embodying this principle have practically replaced the mechanical rectifier discussed in section 19. In the next chapter details concerning this method will be given.

56. Hot Filament X Ray Tube. — Dr W D Coolidge, of the General Electric Research Laboratory was the first scientist to construct an x ray tube of the hot filament type. A tube of this kind differs from the gas tube, not because x rays originate in any different manner but because the stream of high speed electrons has its origin in an incandescent filament. Although there are many varieties of hot filament tubes, certain fundamental principles are utilized in nearly all of them and these the student should clearly understand.

To begin with, we cannot do better than examine the construction and operation of the Universal Coolidge tube one so satisfactory that, after many years of service, it is still on the market in only slightly altered form. Figure 46 is an actual photograph. This type, like almost any other consists essentially of a filament *F* Fig 47 which acts also as the cathode and the anode *A*. To heat the filament, an independent circuit, called the *filament circuit*,

is necessary. In the original arrangement a storage battery B_1 and B_2 was used as the source of supply for this circuit. In the arrangement in actual use, as shown in Fig 48, a branch from the A C mains supplies a small filament step-down transformer, the secondary of which is connected in series



Courtesy General Electric X-ray Corporation

FIG. 46. The Coolidge Universal Hot Filament X-ray Tube.

with the filament. While this arrangement is more convenient it has one disadvantage. Voltage fluctuations on the line will cause corresponding fluctuations in the filament and consequently as we shall see later, alter the milliamperage through the tube.

To give the necessary high speed to the liberated electrons the high tension voltage is applied to the tube in the usual way, the hot filament being, of

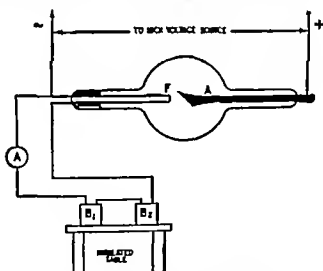


FIG. 47 Simple connections when filament of a hot filament x-ray tube is heated by means of a storage battery

course, negative. Since the whole filament circuit is raised to the high potential of the cathode, it is necessary to insulate the storage battery (or the filament transformer). The complete circuit, therefore, includes (1) the usual high tension circuit, (2) the filament circuit. In Fig 49 connections

for the complete arrangement with mechanical rectifier (minus the synchronous motor circuit) are shown (In the next chapter diagrams of circuits using rectifying valves will be given) It will be seen that the high tension

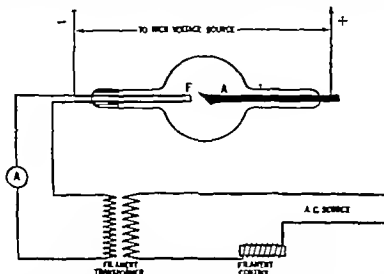


FIG. 48. Simple connections when filament is heated by a step-down transformer

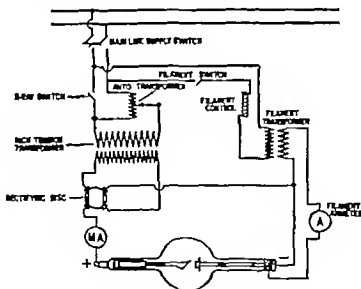


FIG. 49. Complete connections when a hot filament tube is operated with high tension voltage controlled by autotransformer and rectified by mechanical rectifier

circuit, which in this case has autotransformer control, is exactly the same as that already discussed. The new feature is the filament circuit controlled by the filament switch and containing an ammeter to enable an operator to read the current heating the filament. By means of the filament control (a

variable reactance) the strength of the current may be altered. Before discussing details of control, however, it is desirable next to look at one or two further points in connection with the tube itself.

57 Preparation of Hot Filament Tubes. — To obtain the necessary high vacuum and to eliminate as much as possible all traces of residual gas, elaborate precautions are taken. Vacuum workers know that small amounts of gas not only cling to solid surfaces, but are also embedded right inside all materials. For example, if a glass vessel is highly exhausted and sealed off without any preliminary heating, a very slight rise in temperature will release gas from the glass and the vacuum will very quickly deteriorate. In high vacuum work, therefore, such as in the exhaustion of hot filament tubes, a very careful process of degassing must be carried out. Into details of this process it is not necessary to go but we may point out that, with the exhaust pump running "full blast," all metal parts are heated to a high temperature (by electromagnetic induction) the tube itself is baked in an oven at 400°C or 500°C., and a current put through it under operating conditions. Finally the tube is sealed off, after gases occluded in the glass and the metal parts

TABLE VII

Gas	Pressure in Microns Mercury
Helium	5.0 to 10.0
Hydrogen	4.0 to 8.0
Nitrogen	0.5 to 1.0
Water Vapor	0.2 to 0.5
Mercury Vapor	0.01 to 0.03

have been removed as completely as possible. One reason for preventing the temperature of a target rising to too high a value at the focal spot is to avoid the liberation of gas which would otherwise result.

Since a perfect vacuum cannot be obtained, there is always a very slight amount of residual gas, and hence there is always the possibility of a few stray positive ions being formed. Provided the gas pressure is well below the value where cumulative ionization by collision takes place (see section 38) no harm is done. This value naturally depends on the type of tube used, but some idea of its magnitude will be had from Table VII. This table, taken from a paper on x ray tubes by Groes and Atlee, of the General Electric Corporation, gives the maximum permissible pressures in microns* of mercury for satisfactory operation of a 85 K.V.P. (kilovolts peak), 30 ma. tube.

58. Focusing — In section 50 a brief reference was made to the focal spot, the small area on the face of the target against which the beam of cathode

* 1 micron = 0.001 mm.

rays or electrons strike. In the gas x ray tube, the beam is focused on this spot partly because of the shape of the cathode partly because the walls of the tube in the neighborhood acquire a negative charge and this charge exerts a repulsive effect on the beam of electrons. In hot filament tubes focusing is brought about partly because the electric field which exists between cathode

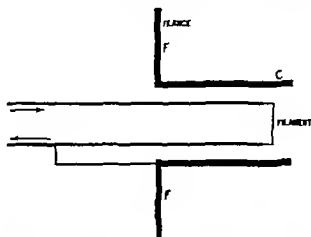


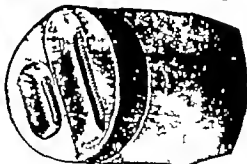
FIG. 50 Focusing device in the universal Coolidge Tube.

and anode directs the beam of electrons towards the target, but more so because of the actual structure of the cathode itself. In the universal tube for example, the filament, wrapped into a small flat spiral, is surrounded by a concentric metal cylinder one end of which projects a little beyond the filament, as shown in Fig 50. The other end is attached to the flange *F*



Courtesy Philips' Gloeilampenfabrieken, Holland

FIG. 51 A focusing arrangement in a hot filament tube.



Courtesy General Electric X-ray Corporation

FIG. 52 A close-up view of filaments in a double filament tube.

As the cylinder and flange, and the filament itself are all in electrical contact with the negative high tension terminal a repulsive force acts on the liberated electrons. A somewhat similar arrangement is shown in Fig 51 a diagram taken from literature of the Philips X ray works. Figure 52 is a close-up photograph showing the actual relation of the filaments, in a special double-

variable reactance) the strength of the current may be altered. Before discussing details of control, however, it is desirable next to look at one or two further points in connection with the tube itself

57 Preparation of Hot Filament Tubes. — To obtain the necessary high vacuum and to eliminate as much as possible all traces of residual gas, elaborate precautions are taken. Vacuum workers know that small amounts of gas not only cling to solid surfaces, but are also embedded right inside all materials. For example, if a glass vessel is highly exhausted and sealed off without any preliminary heating a very slight rise in temperature will release gas from the glass and the vacuum will very quickly deteriorate. In high vacuum work, therefore such as in the exhaustion of hot filament tubes, a very careful process of degassing must be carried out. Into details of this process it is not necessary to go, but we may point out that, with the exhaust pump running 'full blast', all metal parts are heated to a high temperature (by electromagnetic induction) the tube itself is baked in an oven at 400°C. or 500°C., and a current put through it under operating conditions. Finally the tube is sealed off, after gases occluded in the glass and the metal parts

TABLE VII

Gas	Pressure in Microns Mercury
Helium	5.0 to 10.0
Hydrogen	4.0 to 8.0
Nitrogen	0.5 to 1.0
Water Vapor	0.2 to 0.5
Mercury Vapor	0.01 to 0.03

have been removed as completely as possible. One reason for preventing the temperature of a target rising to too high a value at the focal spot is to avoid the liberation of gas which would otherwise result.

Since a perfect vacuum cannot be obtained, there is always a very slight amount of residual gas, and hence there is always the possibility of a few stray positive ions being formed. Provided the gas pressure is well below the value where cumulative ionization by collision takes place (see section 38) no harm is done. This value naturally depends on the type of tube used, but some idea of its magnitude will be had from Table VII. This table taken from a paper on x ray tubes by Gross and Atlee, of the General Electric Corporation, gives the maximum permissible pressures in microns* of mercury for satisfactory operation of a 85 K.V.P. (kilovolts peak) 30 ma. tube.

58. Focusing — In section 50 a brief reference was made to the *focal spot*, the small area on the face of the target against which the beam of cathode

* 1 micron = 0.001 mm.

By means of rheostat or autotransformer control, greater and greater voltages (measured by equivalent spark gap length) were applied to the tube, and for each value the corresponding tube current was measured. It will be noticed that, while at first the tube current increases with increasing voltage,

a stage is reached at which increase in voltage produces no increase in milliamperage. Those who prefer to study results in graphs rather than in tables will see that Curve A, Fig. 53, shows the same result even more clearly. In Table IX and Curve B Fig. 53 the same result is shown for a different filament current, the only difference in the two cases being that the maximum tube current in the latter is greater. Experiment tells us, then, that corresponding to each filament current, there is a maximum value of the tube current, which is independent of the applied voltage.

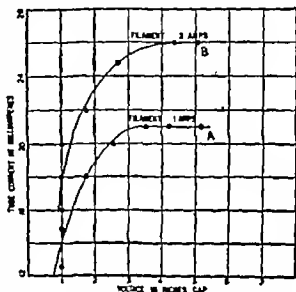


FIG. 53 Graphs showing saturation tube current for two different filament currents.

The explanation of this maximum current—called the *saturation current*—is simple enough. The available supply of electrons from a hot filament depends on its temperature and therefore on the magnitude of the filament current. Evidently no more electrons can be transported across the tube per second than are liberated each second from the filament.

The student may wonder why all the liberated electrons should not be transported to the anode at low as well as at high voltages. The chief reason for this lies in the existence of what is called the *space charge*. Suppose a filament is heated *without* the application of a potential difference between filament and anode. The evaporated electrons then form a cloud of negative electricity in the space immediately surrounding the filament. Since negative electricity repels negative, due to this space charge, there soon develops a strong repulsive force which not only prevents the emission of further electrons but also drives electrons back into the filament. When a comparatively small voltage is applied across the electrodes (with anode positive) the electrons move to the anode and a current is recorded. But with low voltages the speed of the electrons is not great, and they are present in sufficient numbers in the region between the electrodes to continue to exert a backward force on

filament tube, to the surroundings. By using filaments of different shapes and adjusting the relative position of the parts, focal spots of different sizes are obtained.

"The focal spot size, shape, and distribution can be controlled almost entirely by the filament size, shape and position relative to the rest of the cathode structure." (Gross and Atlas)

59 The Anode and Target. — In the universal tube, the anode head is of solid tungsten, whose inclined face forms the target, as shown in Fig 46. No cooling device is added, it being possible to operate the tube with the anode white hot, provided unidirectional voltage is applied.

In sections 62 and 64 reference will be made to tubes of other design.

60 Control of Tube Current. — In the gas tube we have seen that the residual gas is conducting the current consisting of a stream of positive ions in one direction along with cathode rays in the opposite direction. In the hot filament tube the current consists solely of the stream of negative electrons

TABLE VIII — FILAMENT CURRENT
4.10 AMP

Spark Gap	Ma.
1"	13
1"	15
1½"	18
2½"	20
3½"	21
4½"	21
5½"	21

TABLE IX — FILAMENT CURRENT
4.20 AMP

Spark Gap	Ma.
1"	16
1"	18
1"	20
1½"	22
2½"	25
3½"	25
4½"	26
5	26

liberated from the filament. How is the magnitude of this current controlled? In order to understand the answer to that question it is well to recall that an electric current is measured by the total quantity of electricity passing each second any point on the circuit. If therefore more electrons are transferred every second from the filament to the target, the tube current will be greater. Now work on the thermionic emission has shown that the higher the temperature of the hot filament the greater the supply of electrons. *The milliamperage through the tube therefore is increased simply by increasing the filament heating current.* But, it is asked where does voltage come in? That can be answered with reference to experimental results such as given in Tables VIII and IX (taken from Wappler Electric Co literature). The numbers in Table VIII refer to a tube whose filament current was kept constant at 4.10 amperes.

By plotting these results an extremely useful curve similar to that in Fig 54 will be obtained. Figure 55 is a copy of a similar curve for a Universal tube taken from advertising literature

Although an increase in voltage beyond the value necessary to produce saturation does not alter the magnitude of the tube current, it does alter the nature of the beam of x rays. (See section 84) Moreover an increase in voltage beyond this point means an increase in the electrical power supplied the tube. Care should be exercised therefore not to exceed the maximum voltage and maximum power which is safe to use with a particular tube. (See section 65)

61 Voltage Stabilizer — In connection with the relation between filament current and tube current it is important to note that a very slight change in the filament current may produce a big change in the tube current. If we take some actual numbers from the curve of Fig 55 we see that with filament current 4 amperes, the tube current is 40 ma while an increase to $4\frac{1}{4}$ amperes raises the tube current to 100 ma. This has an important practical aspect. Should the filament current fluctuate there will be marked changes in the tube current — as much as a 25 per cent change for a 1 per cent change in filament current. Obviously this is not desirable.

If storage batteries are used as the source of supply for the filament circuit, voltage fluctuations are negligible. Unfortunately however storage batteries are not so convenient as a filament transformer and the latter is almost entirely used. The supply for the transformer is commercial A.C., and in this case voltage fluctuations are inevitable. Most readers will have observed a sudden dimming of incandescent lights when, perhaps in another part of the house, an electric iron or toaster is turned on. The voltage applied to the lamps has lowered because of the greater load put on. Now such sudden changes in voltages are almost inevitable when working with a supply used for many purposes and in many places. In using a hot filament tube with filament transformer therefore, and with no special means for getting rid of voltage fluctuations, marked changes in milliamperage may occur.

By means of a voltage stabilizer however it is possible to maintain a constant tube current in spite of voltage fluctuations.

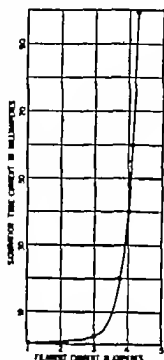


FIG 55 Graph showing that a slight change in filament current may cause a marked change in tube current.

those electrons near the filament. For a given field between the electrodes and a fixed filament temperature, a balance is reached when electrons are emitted from the filament at such a rate that the force on those near the filament due to the space charge cancels the applied electric field.

As higher and higher voltages are applied, a greater and greater number of electrons is transported each second across the tube until ultimately all the

TABLE X

Filament Current	Tube Current
3.09 amp.	0.6 ma.
3.31	2.5
3.40	4.4
3.50	8.2
3.57	12.6
3.67	20.7
3.65	21.8
3.71	27.0
4.13	35.4

electrons emitted by the filament reach the anode. As already noted we have then the saturation current. In operating an x ray tube, invariably the applied voltage is sufficiently high to ensure saturation current. In that case, we cannot emphasize too strongly the electron or tube current depends only on the temperature of the filament, that is, on the magnitude of the current used to heat it.

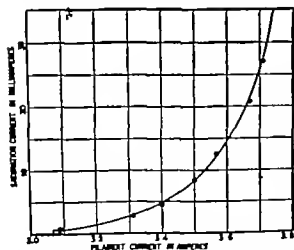


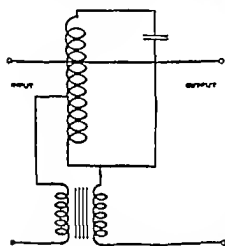
FIG. 54. Graph showing how the saturation tube current varies with the filament current.

Control of the tube current, therefore, for all practical purposes, depends solely on regulation of the filament current whose magnitude may be read directly from the filament ammeter. It is, then, highly desirable that the operator of a particular tube should know the tube (saturation) current corresponding to each ammeter reading. Such information he can readily obtain for himself by taking for each of several filament current values, the saturation tube current. He

will then have a table similar to Table X (a copy of some actual results taken from an early paper by Dr. W. D. Coolidge)

tacts or for fixed tension the farther away the electromagnet, the greater the tube current.

Considering now the filament circuit as a whole, we see that it has two possible resistance values (1) a high value when the contact at *P* is open and the resistance *R* is the only path between *A* and *B* and (2) a low value, when the contact is closed, and *R* is shunted by a very low resistance. In actual use, when the electromagnet and the spring are set for a desired tube current, and the circuits are closed the interrupter is in a state of rapid vibration the resistance of the filament circuit alternating between the high and the low values. There is then a resultant average value for the net



Courtesy General Electric X-ray Corporation

FIG. 57 To illustrate the principle of a constant voltage stabilizer. For a 12 per cent variation in voltage on the input side, the output voltage varies only 1 per cent.

resistance and hence with steady applied voltage both filament and tube currents remain constant. If the line voltage suddenly increases, the milliamperage through the tube does not increase because the high resistance *R* is thrown in for a longer portion of the total time and so the average filament resistance increases, thus compensating for the rise in voltage. On the other hand, if the voltage drops, the contact points at *P* remain closed for a longer fraction of the time the average filament resistance becomes less, and once more the tube current remains constant.

The Kearley stabilizer it will be noted, maintains a constant tube current by automatic control of the filament current. The *constant voltage stabilizer* another type

which in some respects is more suitable for the type of x ray apparatus now on the market, is so designed that, when a fluctuating line voltage is applied to the input side of the stabilizer an almost steady voltage can be taken off the output side. A good stabilizer of this kind shows a variation of only 1 per cent in the output voltage when the input fluctuates as much as 12 per cent. It is not easy for anyone not trained in electrical engineering to understand fully the operation of this type of stabilizer but the diagram in Fig 57 will give a general idea of the arrangement used. For this diagram the author is indebted to Mr W C Baldwin manager of the Engineering Service of the General Electric X ray Corporation. Mr Baldwin states that their product, the Universal Stabilizer as most other stabilizers basically consists of a saturated core reactor and an air gap reactor run well below saturation

The student will understand that any arrangement in which resistance or impedance increases (or decreases) in step with an increase (or decrease) in voltage will maintain a constant current in any ordinary circuit. For example there is a type of lamp (using iron wire in an atmosphere of hydrogen) which gives the same current for a wide range of applied voltages. This is because the resistance of the lamp increases with rise in temperature and hence with an increase in the power supplied. In this special lamp the increase in resistance just compensates for the increase in voltage. This principle of adding resistance when the voltage goes up is utilized in the *Kearsley Stabilizer*.

This stabilizer, designed by Kearsley of the General Electric, makes use of a mechanical device which automatically throws more resistance in the

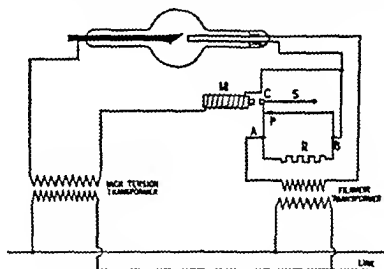


FIG. 56. To illustrate the operation of the Kearsley Stabilizer

filament circuit when the voltage rises and cuts out resistance when the voltage drops. The stabilizer in actual use is not quite so simple as that shown in Fig 56 but this diagram will make clear its basic principle. It will be noted that the filament circuit includes the secondary of the filament transformer the filament itself and a resistance R in parallel with a branch APB of very low resistance. This branch circuit is sometimes open sometimes closed, because it contains an interrupter similar to the hammer break of an induction coil controlled by the electromagnet M in the high tension tube circuit. When a tube current is flowing M is magnetized the soft iron piece C is attracted, and the contact at P is broken provided the pull on C is great enough to overcome the tension of the controlling spring S . The greater the tension of this spring, the greater the tube current necessary to separate the con

which at each end is sealed to the re-entrant glass cylinders G G . A window W placed opposite the target permits the passage of all but the softest x rays. The protection provided by the central metal cylinder is greatly increased by a layer of lead which surrounds it. In addition the somewhat massive anode and the cathode assist in cutting off unwanted rays, particularly longitudinally and a layer of bakelite which forms the casing of the whole tube adds more protection. At the same time this casing shields the bright light of the incandescent filament and mechanically is a protection to the glass.

The General Electric X ray Corporation have a tube, somewhat similar in appearance in which an all glass cylindrical envelope is surrounded by a removable casing providing both protection and insulation.

63 Line Focus. — The metalix tube introduced another new feature in x-ray tubes, and that was the use of a linear instead of a circular spot, a suggestion originally made by Goltze. To understand the significance of this change, the student must be clear about two points. The first has to do with the intense local heating generated at the focal spot. (Recall section 53)

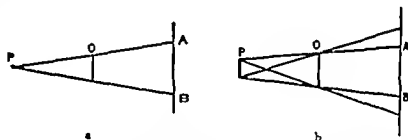


FIG. 60. In (a) the small source of light P casts a sharp shadow of the obstacle O . In (b) the broad source gives rise to the deep shadow AB surrounded by a penumbra.

Concerning this, it should be evident that the *larger* the area over which this heat is developed, that is, the larger the focal spot, the lower the resulting temperature and the less the danger of destroying the tube. The second point concerns the relation of the size of the focal spot to the sharpness of the picture when the shadow of an object is observed on a fluorescent screen or a photographic plate. If the student will think of x rays as invisible light (as indeed they are) he will realize that the *smaller* the dimensions of the source of the beam, the sharper the shadow picture of an object, unless it is a flat one placed close to the screen or plate. Figure 60 which illustrates the point, will be very familiar to anyone who has taken a course in elementary light. For sharp detail, therefore the focal spot should be as small as possible.

But if the focal spot is very small, the power input (the load on the tube) must be kept small because of the temperature effect, and frequently

62. X Ray Protection and Metalix Tube. — Although a detailed discussion of the properties of x rays has not yet been given probably all medical students are aware that unwanted x rays falling on the body of either patient or operator may have serious injurious effects. It is very necessary, therefore, to provide adequate protection against such rays. To do this many precautions must be taken (see section 87), but obviously the first step is to see that, if possible, the beam of rays leaving the tube is restricted to a narrow bundle. To some extent this can be accomplished by surrounding the bowl of the tube with some material which absorbs all or nearly all the

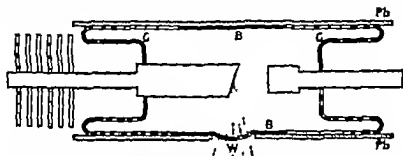


FIG. 58. Schematic diagram of metalix x-ray tube.

rays which strike it. An opening of course, must be left to allow the passage of the useful cone of rays. Some of the earlier tubes were so covered with a protecting covering of rubber impregnated with lead oxide, lead being an excellent absorbing material for ordinary x rays, or with a protecting bowl of thick lead glass.

A radical departure in x ray tube protection and in tube design was embodied in the so-called *metalix* tube, first put on the market by the Philips Gloeilampen



Courtesy Philips Gloeilampenfabriek X-Ray Works

FIG. 59 The Metalix x-ray tube.

fabriek X ray Works, Holland. Although Coolidge as early as 1915 had experimented with a metal tube, the metalix was the first, which used the principle of metallic protection in the tube itself to be put in the hands of radiologists. The main features of this type will be understood by a study of Fig 58 and Fig 59 which shows its general appearance. The tube consists essentially of a cylinder of chromium-iron alloy, *B* in Fig 58,

tron beam strikes the beveled edge of this disc, clearly shown in Fig 63 giving rise (along the center of the useful beam of rays) to an *effective* spot which in one tube, is $2 \text{ mm} \times 2 \text{ mm}$ when the actual area over which heat is produced is 7 mm (the length of the actual spot) $\times 190 \text{ mm}$ (the mean circumference of the annular area) With such a tube therefore, high power inputs are



Courtesy General Electric X-ray Corporation

FIG. 63 A rotating anode tube.

possible without losing the advantages of a small focal spot. For example with a certain tube of this type with an effective focal area as small as $1 \text{ mm} \times 1 \text{ mm}$ it is possible to use the same power input and same exposure time as for an effective spot of $3.8 \text{ mm} \times 3.8 \text{ mm}$ with a stationary anode

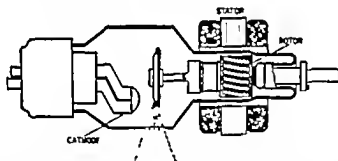


FIG. 64 Diagram showing the essential features of a rotating anode tube.

65 Rating — From the preceding sections, it should be evident that it is highly desirable to know the maximum power which may safely be supplied to a tube, as well as the time this or any lesser amount may be used. This is what is meant by *rating*.

In considering this question the student should realize that only a very small fraction of the total energy supplied a tube goes into the energy of the x ray beam. The remainder which goes into heat, is a "dead loss," and, as we have already pointed out in section 53 steps must be taken to remove that heat sufficiently rapidly to prevent injury to the tube. In that section reference has been made to most of the ways in which rapid rise in temperature is prevented. Note again Figs. 59 and 65 in which the tubes are equipped with radiator fins to dissipate the heat conducted along the anode and Figs. 66 and 67 illustrating tubes provided with water cooling. Note also, Fig 68,

it is not desirable to restrict the power. For example, the smaller the power, the longer the exposure when x ray photographs are made; and in many cases it is necessary to have short exposures.

Designers of x ray tubes, therefore, were faced with the problem of combining sharp shadows with short exposures, or in other words, of retaining the equivalent of small focal spots with adequate power input. The problem was solved in two ways, (1) by the use of a *line* focal spot, as in the metalix tube and (2) by the use of a rotating anode (see section 64)

In the metalix tube and many others since placed on the market, a linear filament is so placed in relation to the surrounding cathode that a focal spot of the shape *AB* Fig 61, is formed on the face of the target *TT'*, this face being inclined to the axis of the tube at an angle of 71° not the 45° previously used with circular spots. Now although the actual length of the focal spot is several times

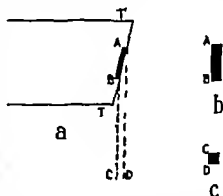


FIG. 61 *AB* represents the actual area of the focal spot, *CD* the projected area looking along the dotted line.

its width, to an observer looking along the central part of the beam of x rays, its *effective* length, in so far as its ability to cast shadows is concerned, is only *CD*. Thus, although the actual total area of the spot is as illustrated in Fig 61*b* its effective "shadow-casting" area is more like Fig 61*c*. Because of the greater actual area, it is possible to use an electric load on the tube considerably greater than when a spot of actual area Fig 61*c* is formed on a 45° face target.

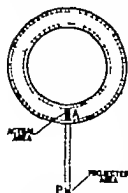


FIG. 62. The heavy circles represent the bevelled edge of a rotating anode, *A* being the actual area of the focal spot.

64 Rotating Anode.—To permit the use of still higher amounts of power tubes with revolving anodes have been designed by both the Philips X ray Works and the General Electric X ray Corporation. In tubes of this kind, although the focal spot is stationary and of the rectangular shape shown by the black spot *A* in Fig 62, because the anode is kept in rotation the area over which heat is developed is the annular space shown in this figure by the dotted circles. In the General Electric tube illustrated in Fig 63 and Fig 64 a disc of tungsten is rotated at a speed of 3000 r.p.m. by an induction motor whose stator is outside the evacuated part of the tube. The elec

which shows clearly a massive blackened cooling sphere at the end of an anode which itself has a high thermal capacity. The student will recall that black bodies are good radiators, and that the higher the thermal capacity of a substance, the lower the temperature rise for a fixed amount of heat.



Courtesy General Electric X-ray Corporation

FIG. 65. A radiator x-ray tube.



Courtesy Philips Gloeilampenfabrieken X-ray Works

FIG. 66. A water cooled x-ray tube.

The actual quantity of heat developed is directly proportional to the total energy put into the tube and that, it will be remembered depends on the product voltage \times current \times time. (Recall VIt joules in ordinary circuits.)



Courtesy General Electric X-ray Corporation

FIG. 67. A water cooled x-ray tube.



Courtesy Philips Gloeilampenfabrieken X-ray Works

FIG. 68. An x-ray tube with a massive anode and blackened cooling sphere.

If, then a radiologist is told that a certain tube can be safely operated for 30 seconds, at 85 kilovolts peak (Kv P) with a current of 30 ma., he has a rating which is simple and definite. But it does not give enough information. He may want to know how long the tube may be used with 5 ma. at the same

or some other KvP or he may wonder how the rating is altered when a change is made in the operation of the tube from a constant voltage generator to one in which energy is utilized only in alternate half-cycles (see next chapter)

Modern practice gives the answer to such questions because the manufacturer supplies charts from which exposure times can be read off for corresponding voltage and current values, a separate chart being supplied for each type of

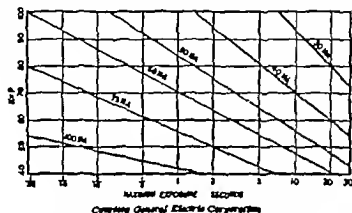


FIG. 69 A typical rating chart.

supply equipment, such as full wave half wave. (Again see next chapter) Figure 69 taken from General Electric literature is an example of one of the actual charts for the Coolidge Tube unit DX2-45. It applies when a 2.0×2.0 mm. focal spot is used and the tube is operated on full wave rectified equipment. To make sure that he understands the use of such a chart, the student should check the values given in Table XI. These are read off one of the graphs of Fig. 69

TABLE XI

KvP	ma.	Exposure Time
100	60	$1/20$ sec.
86	60	$1/5$
70	60	1
54	60	5
40	60	20

It is important to note that, although the exposure time in the first line of this table is 400 times less than that in the last line, the power supplied the tube is only $2\frac{1}{2}$ times greater. In other words, it is a bad mistake to assume that if it is permissible to expose for 1 second with a certain amount of

which shows clearly a massive blackened cooling sphere at the end of an anode which itself has a high thermal capacity. The student will recall that black bodies are good radiators, and that the higher the thermal capacity of a substance, the lower the temperature rise for a fixed amount of heat.



Courtesy General Electric X-ray Corporation

FIG. 65 A radiator x-ray tube.



Courtesy Philips Gloeilampenfabrieken X-ray Works

FIG. 66 A water cooled x-ray tube.

The actual quantity of heat developed is directly proportional to the total energy put into the tube and that, it will be remembered, depends on the product voltage \times current \times time. (Recall VI joules in ordinary circuits.)



Courtesy General Electric X-ray Corporation

FIG. 67 A water cooled x-ray tube.



Courtesy Philips Gloeilampenfabrieken X-ray Works

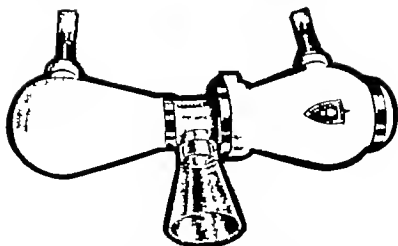
FIG. 68. An x-ray tube with a massive anode and blackened cooling sphere.

If then, a radiologist is told that a certain tube can be safely operated for 30 seconds, at 85 kilovolts peak (Kv P) with a current of 30 ma., he has a rating which is simple and definite. But it does not give enough information. He may want to know how long the tube may be used with 5 ma. at the same



Courtesy General Electric X-ray Corporation

FIG. 70. A shockproof x-ray tube.



Courtesy Philips Gloeilampenfabrieken X-ray Works

FIG. 71. A shockproof x ray tube.

power, that five times that amount could be used for a fifth of a second. Time must be allowed for heat developed to be removed, hence a greater and greater limitation is placed on the permissible power the shorter we make the exposure.

66. Shockproof Tubes. — In section 62 reference was made to the necessity of protecting a tube so that x-rays do not leave it in unwanted directions. Protection against electrical shock arising from contact with high tension wires is equally important. For a great many years both the electrical leads to a tube and its terminals were unprotected and there was always present very real danger of bad electrical shocks to patient and operator because of accidental contact with these conductors. Nowadays, although this danger is still often present, many tubes are *shockproof* that is, they are so protected that it is perfectly safe to put one's hand on the casing in which the tube is housed.

Figures 70 and 71 illustrate the general appearance of two such tubes. The means of providing protection is extremely simple. The tube proper is enclosed in a metal case which is grounded, and the high tension leads to the tube are surrounded by heavy insulating material around which a flexible grounded metallic casing is wrapped.

67 Oil immersion. — The design and general arrangement of the earthed casing of a shockproof tube must be such that there is no danger of breakdown sparking between any high tension part of the tube and the surrounding casing. In Fig 71 a Philips' tube this is done by suitable design of the parts. In Fig 70 a General Electric tube, the space between the tube and the casing is filled with oil the whole being hermetically sealed. Because of its insulating properties oil minimizes the space necessary between high tension and earthed parts. The use of oil also makes the arrangement independent of atmospheric conditions, and, moreover "oil is superior to air as a heat absorbing and cooling medium.

In this connection it is interesting to note that the General Electric Corporation have units in which not only the x ray tube, but also the high voltage equipment, transformer and all, are enclosed in oil in a grounded container.

68. Low Voltage Tubes. — A tube operated on voltages of the order of 50 000 volts has been designed largely because of the work of Chaoul, for the treatment of both malignant and nonmalignant skin diseases. The important feature of the Chaoul tube is the anode end. The electrons, indicated by the dotted lines in Fig 72, pass down an earthed metal cylinder and strike

CHAPTER VII

VALVE RECTIFICATION

69 Self rectifying Tubes. — We have already emphasized that electrons leave a hot filament only when it is negative. Hence, if a tube such as the Universal Coolidge is placed directly across the high tension terminals of a transformer current ordinarily passes only when the end of the secondary of the transformer which is attached to the anode, is positive. In the next half-cycle, when this end is negative no current passes. Provided certain precautions are observed, therefore, a tube can act as its own rectifier and so be used with the simple arrangement shown in Fig 73. This is known as *self-rectification*.

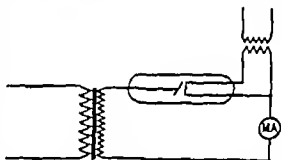


FIG. 73. An x-ray tube acting as its own rectifier

In Fig 74 graph (a) represents the theoretical wave form of the voltage applied to the tube, and (b) shows the theoretical* corresponding tube current. Note that it is intermittent but unidirectional.

In actual practice, in the great majority of cases, it does not do to let a tube act as its own rectifier. As we have already pointed out more than once, the focal spot on the target may become very hot. In the Universal tube the whole anode sometimes becomes white hot. Now any metal emits thermionic electrons at high temperatures, hence if an alternating high tension potential is applied to the tube there is always the danger that, during the half-cycle when the anode is negative it will emit electrons due to a high temperature. Such an emission is disastrous to the tube. In addition to causing the liberation of unwanted x rays from places where these electrons strike this beam from a hot anode may destroy the tube by the damage it does on impact. More often than not, therefore hot filament tubes are operated

* By means of oscillographs the actual form of the curve can be obtained. Although it departs somewhat from the smooth type of curve shown in Fig 74 the form of the current graph obtained by the oscillograph shows clearly the suppression of each half cycle.

at its far end a target *T*, made of gold-plated nickel, only 0.15 mm. thick. Water circulating in a narrow region around the target end of the cylinder effectively cools the target. Because of the extremely small thickness of the target, the x rays generated pass through it with slight absorption, as well as through the 2 mm. thickness of water between the target and the outer wall *W*. A conical applicator *CC* slipped over the end of the tube rests on the skin of a patient, the rays striking the skin at focal distances of only a few centimeters.

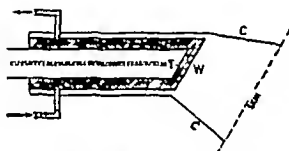


FIG. 72. The target and treatment end of a Charoul therapy tube.

In Chapter VIII, further information will be found concerning the nature of the rays leaving this tube as well as another low voltage tube suitable for producing Grenz rays. In this tube the applied voltage is of the order of 10 000 volts.

In this chapter we have tried to explain the principles involved in the use of hot filament tubes. No attempt has been made to describe the details of every kind of tube on the market, but it is hoped that the main ideas utilized in any kind have been made clear. Our attention has been confined to an explanation of the design and the operation of tubes. Later we shall discuss such questions as the effect of voltage on the nature of the rays leaving a tube.

CHAPTER VII

VALVE RECTIFICATION

69 Self rectifying Tubes. — We have already emphasized that electrons leave a hot filament only when it is negative. Hence, if a tube such as the Universal Coolidge is placed directly across the high tension terminals of a transformer current ordinarily passes only when the end of the secondary of the transformer which is attached to the anode, is positive. In the next half-cycle when this end is negative no current passes. Provided certain precautions are observed therefore a tube can act as its own rectifier and so be used with the simple arrangement shown in Fig 73. This is known as *self-rectification*. In Fig 74 graph (a) represents the theoretical wave-form of the voltage applied to the tube, and (b) shows the theoretical* corresponding tube current. Note that it is intermittent but unidirectional.

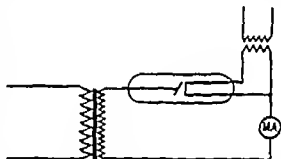


FIG. 73. An x-ray tube acting as its own rectifier

In actual practice, in the great majority of cases, it does not do to let a tube act as its own rectifier. As we have already pointed out more than once the focal spot on the target may become very hot. In the Universal tube, the whole anode sometimes becomes white hot. Now any metal emits thermionic electrons at high temperatures, hence, if an alternating high tension potential is applied to the tube, there is always the danger that, during the half-cycle when the anode is negative it will emit electrons due to a high temperature. Such an emission is disastrous to the tube. In addition to causing the liberation of unwanted x rays from places where these electrons strike, this beam from a hot anode may destroy the tube by the damage it does on impact. More often than not, therefore hot filament tubes are operated

* By means of oscillographs the actual form of the curve can be obtained. Although it departs somewhat from the smooth type of curve shown in Fig 74 the form of the current graph obtained by the oscillograph shows clearly the suppression of each half cycle.

on voltage which has been rectified, and invariably the rectifiers used are of the valve type not the mechanical rotating disc described in section 19

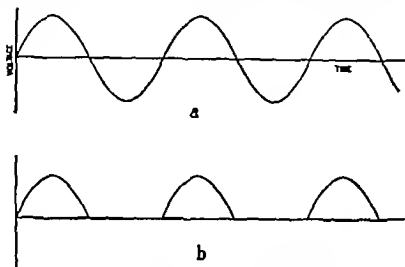


FIG. 74. In self-rectification, or half-wave, tube current flows only in alternate half-cycles.

70 Valve Rectifiers. — As long ago as 1915 Dr Saul Dushman of the General Electric Research Laboratory designed a rectifying valve for use in x ray circuits, to which the name *kenotron* was given. The simple arrangement utilizing a rectifying valve is shown in Fig. 75, where a single valve *V*

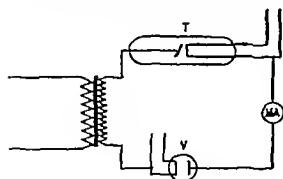


FIG. 75. Half-wave rectification by means of a single valve *V* in series with the tube *T*.

is in series with the secondary of the high tension transformer and the tube *T*. It is well to note that, in order to avoid confusion in all our diagrams we represent a valve by a circular diagram and an x ray tube by a cylindrical one. Actually they may both be cylindrical in shape.

Although in one sense a rectifying valve and a hot filament x ray tube are essentially the same, each with an anode and a hot filament cathode and each permitting the flow of electrons only when the filament is hot and when it is negative, nevertheless there are important differences. A tube is primarily for the production of x rays, whereas in a good valve, x rays must not be generated. To avoid their production the electrons must not be allowed to cross the valve at high speed, or in other words, the voltage drop across the

valve must be small. This is also desirable, because the greater the voltage drop across a valve placed as in Fig 75, the less the voltage available for the tube.

In a good valve, then the aim is to pass a high current at a low voltage. To insure this the valve must be so designed that the current through it is considerably below the saturation value. In section 60 the meaning of saturation current for an x ray tube was explained, use being made of the graphs of Fig 53. Because of the fundamental similarity between a tube and a (vacuum) valve, the same type of graphs apply to a valve. In fact,

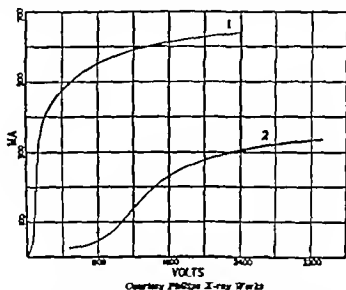


FIG 76. Characteristic curves for two rectifying valves, 1 metalix, 2 glass.

Fig 76 taken from literature of the Philips Metalix Company shows two similar graphs for two different types of rectifying valves. A glance at graph 1 will show that the valve to which this applies will pass a current of 300 ma. when the voltage across it is less than 200 volts, a very small amount compared with tube voltages.

71 Types of Valves. — The original kenotron and the kind of valve first put on the market by the Philips X ray Works were simple diode tubes, consisting essentially of the filament (and associated cathode) and the anode in a highly exhausted glass container. In some respects this arrangement proved unsatisfactory because with an unprotected filament, a negative charge collects on the inner surface of the glass walls, and this makes the valve erratic in its behavior. To quote from General Electric literature "this charge (the charging of the walls) produces a grid action which under variable circuit

conditions may produce a voltage drop as high as 10,000 to 20,000 volts."

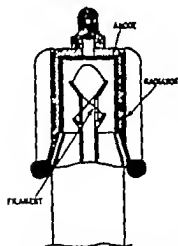
To overcome this defect, different devices have been used. For example, the General Electric now use "a cylindrical anode with a spiral filament inside." Since the filament is thus surrounded, no negative charge accumulates on the glass container as all the electrons are caught by the anode. Figure 77 is a photograph of a kenotron of this type.



Courtesy General Electric X-ray Corporation

FIG. 77 A kenotron, (rectifying valve) with cylindrical anode surrounding a spiral filament.

The Philips Metalix Company have overcome the difficulty by making one end of the valve a metal cylindrical cap, which fulfills the double function of forming part of the container and acting as the anode. This anode 'incloses the filament in all directions except in that of the insulating stem which supports the filament.' The general arrangement is shown in Fig 78. In Fig 76 curve 1 applies to a metalix valve of this sort, curve 2 to one with a glass envelope, the filament current in each case being the same. The marked superiority of the metalix valve is obvious.



Courtesy Philips X-ray Works

FIG. 78. Diagram of a rectifying valve with metal anode surrounding the filament.

Figure 79 shows the external appearance of a valve of a different kind, recently put on the market by the Philips Company. In this type residual gas is left in the valve and use is made of cumulative ionization by collision. Just as in the high vacuum type, electrons are emitted from the filament (of the dull emitter type) when it is negative, but the current is no longer a pure electron stream for the gas is ionized by the colliding electrons. On the reverse half-cycle when the filament is positive there is no electron emission and

no ionization. In this type the manufacturer states that "the voltage drop across it remains constant at a figure of the order of 50 volts" and that "hollow intermediate conductors, situated at intervals along the interior of the discharge tube are interconnected by condensers which encircle the unit and perform the function of distributing the potential by equal stages along

the length of the valve." Currents as high as 1000 ma. are possible with this kind of valve.

72. Half wave Rectification. — Attention has already been directed to Fig 73, the simple self rectified circuit, and to Fig 75 where a single rectifying valve in series with the tube gives rectification and added protection. To each of these circuits Fig 74 is applicable. With the arrangement shown



Courtesy Philips X-ray Works

FIG. 79 A rectifying valve which will carry currents as high as 1000 ma.

in Fig 75 however it is possible to use greater amounts of power than if the tube were its own rectifier. This figure illustrates the simplest case of *half-wave rectification*

73. Full wave Rectification. — Figures 80a and 80b illustrate a type of rectified circuit in common use, the so-called Graetz circuit. In Fig 80a

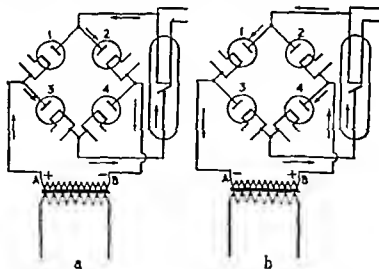


FIG. 80. The Graetz circuit for full wave rectification.

the arrows indicate the direction of the current during the half-cycle when the end *A* of the secondary of the high-tension transformer is positive and the end *B* negative. Figure 80b applies to the alternate half-cycles when *A* is

negative and B positive. If the student will remember that current will traverse a valve only when the filament is negative, he should have no difficulty in showing that in Fig 80a, valves 1 and 4 are not in use, or in Fig 80b, valves 2 and 3, but that in each case current passes through the x ray tube. With this arrangement, therefore, use is made of each half-cycle, the theoretical form of the current being as shown in Fig 81

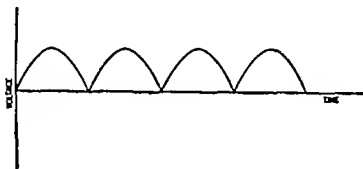


FIG. 81 In full-wave rectification there is tube current every half-cycle.

74 Tube Rating and Type of Rectification.—In Fig 69 an example of a rating chart for a certain tube was given. Now, as a matter of fact, the graphs in this chart were only applicable when this tube was operated on full wave equipment, and, in the manufacturer's literature two other charts were given for the same tube, one applicable to half wave, the other to self rectified equipment. In explaining why a different chart is needed for each type of equipment, it is instructive to look at a concrete case.

From the three charts supplied by the General Electric Company for their RB 1-4 tubes (with small focal spot) one finds out that, when one of these tubes is operated on 60 000 volts, with 20 ma. current, the maximum permissible exposure time is 40 seconds for full wave equipment, 15 seconds for half wave, and 2 seconds for self-rectification. It is not difficult to see why with self rectified use the same amount of power can be used for a much shorter time than with half wave rectification. Without the valve, there is danger of inverse current through the tube, once the focal spot reaches a certain temperature. The presence of the valve, however, does not allow any current to flow even when the focal spot reaches this or a higher temperature.

It is not so easy to see why the permissible time for operation on full wave is longer than on half wave. To understand the reason the student must be clear about the difference between the current recorded by the milliammeter in the tube circuit, and the actual value it may attain in a half-cycle. Consider half wave rectification, where the current is completely suppressed every alternate half-cycle, and where an oscillograph shows the intermittent, pulsating

nature of the current, somewhat as in Fig 82 curve *a*. The current changes, however are much too rapid (remember that the time of a half-cycle is $1/120$ second for a 60 cycle per second supply) to be registered by the moving parts of a milliammeter and this instrument records only a steady mean, of magnitude considerably less than the highest values reached every alternate cycle. In Fig 82 the line *b* represents the steady mean current recorded by the milliammeter. It follows that, if a milliammeter records, say 20 ma., the

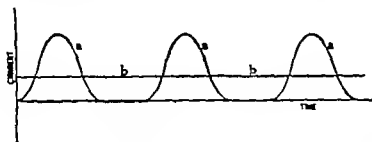


FIG. 82. The line *b* represents the steady current recorded by a milliammeter in half-wave rectification.

current through the valve and the x ray tube may actually attain a value several times 20 ma. — at least three times as great, according to information taken from Philips' literature.

Now consider full wave rectification as depicted in Fig 83. In this case because current passes through the tube *every* half-cycle the mean milliamperage is much nearer the peak value, this being only one and a half

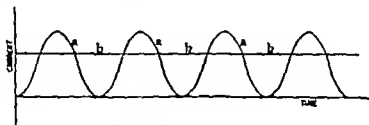


FIG. 83. The line *b* represents the steady current recorded by a milliammeter in full-wave rectification.

times as great as the mean. Thus for a milliammeter reading of 20 ma. the actual tube and valve current may be as high as 60 ma. for half wave rectification and about 30 ma. for full wave. Hence although the total power supplied a tube in each case may be the same (an average of 20 ma. at a peak voltage of 60 000) in the case of half wave equipment, it is given in "doses" which are much more intense, but half as frequent as in the case of full-wave. Since heat generated at the focal spot takes an appreciable time to be dissipated, this means that higher focal temperatures are reached

with half wave than with full wave, with consequent shorter permissible times of tube operation

75 The Use of Condensers with Valves.—Consider a circuit arranged as in Fig 84, where *C* represents a condenser of fairly high capacity and one capable of withstanding x ray potentials. During the half-cycle when *A* is positive and *B* negative, as in Fig 84*a*, current can flow both through the x ray tube and into the condenser, charging it as indicated in the diagram, the potential difference across the condenser being the same as across the tube. During the next half-cycle, as represented in Fig 84*b*, no current can flow

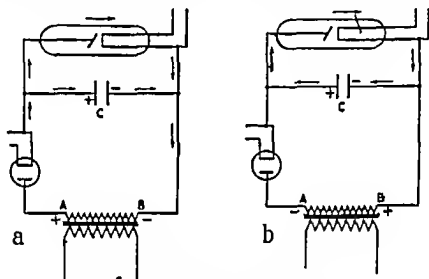


FIG. 84. To illustrate the use of a condenser for applying an approximately constant potential across an x-ray tube.

from the transformer because the negative end of its secondary is attached to the anode side of the rectifying valve. During this half-cycle, however, the condenser can discharge through the tube, with a drop in voltage which is small compared with the maximum potential to which it was charged. To understand why the voltage drop is small, let us make an estimate using actual numerical values.

Suppose the average tube current during this discharge of the condenser is 20 ma. and that the capacity of the condenser is 0.1 microfarad. Then during a half-cycle of $1/120$ of a second, the quantity of electricity which leaves the condenser

$$\begin{aligned}
 &= \frac{20}{1000} \times \frac{1}{120} \text{ ampere seconds or coulombs} \\
 &= \frac{1}{6000} \text{ coulomb.}
 \end{aligned}$$

But, since the capacity of the condenser is $\frac{1}{10}$ mf or $\frac{1}{10} \times 10^{-6}$ farad, if V is the voltage drop, the quantity of electricity which leaves the condenser also

$$= \frac{1}{10} \times 10^{-6} \times V \text{ coulomb.}$$

$$10^{-7}V = \frac{1}{6000}$$

or

$$V = 1667 \text{ volts.}$$

Compared with the peak voltage developed in the secondary of the transformer this is slight.

With the above arrangement, then the voltage applied to the tube will remain moderately steady somewhat as represented in Fig 85 a copy of a diagram published by Watson and Sons (Electro-medical) Limited, London

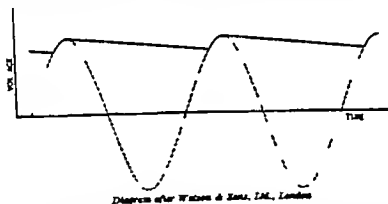


FIG. 85 With the arrangement shown in Fig. 84 the drop in tube voltage is slight.

76. The Greinacher Circuit.—In the above arrangement we have noted that during every alternate half-cycle the transformer does not supply any power to the circuit. Actually condensers and valves are used in less simple arrangements. The Greinacher circuit shown in Fig 86 is an example of one arrangement which has been widely used. In it, by the use of two condensers and two valves, (1) the transformer is utilized every half-cycle (2) the voltage drop across the tube is slight; and (3) approximately twice the transformer voltage is applied to the tube.

By reference to Fig 86 it will be seen that, during the half-cycle when A is positive and B negative, condenser C_1 is charged to the maximum voltage developed in the secondary of the transformer whereas on the alternate half cycle, when A is negative and B positive, C_2 is similarly charged. Once the

with half wave than with full wave, with consequent shorter permissible times of tube operation

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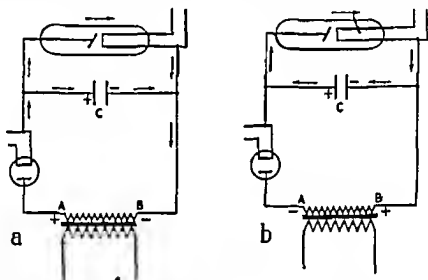


FIG. 84. To illustrate the use of a condenser for applying an approximately constant potential across an x-ray tube.

from the transformer because the negative end of its secondary is attached to the anode side of the rectifying valve. During this half-cycle, however the condenser can discharge through the tube with a drop in voltage which is small compared with the maximum potential to which it was charged. To understand why the voltage drop is small let us make an estimate using actual numerical values.

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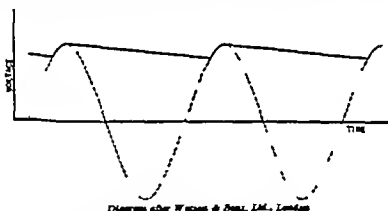


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By reference to Fig 86 it will be seen that, during the half-cycle when A is positive and B negative, condenser C_1 is charged to the maximum voltage developed in the secondary of the transformer whereas on the alternate half-cycle when A is negative and B positive, C_2 is similarly charged. Once the

condensers are charged, *each* of them can send a current through the x-ray tube, since in the circuit 1 2 3 4 the condensers and the tube are in series. Moreover, just as explained in the previous section, the voltage drop in each half-cycle will be slight. Again, since each condenser is charged to the transformer voltage and the two are in series with the tube, the tube voltage is approximately twice that of the transformer

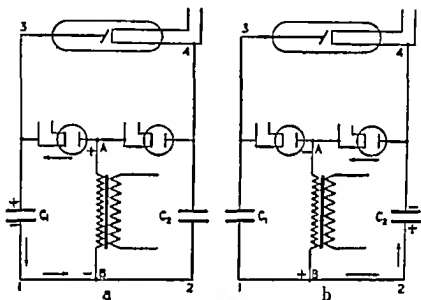


FIG. 86. The Greinacher constant potential circuit.

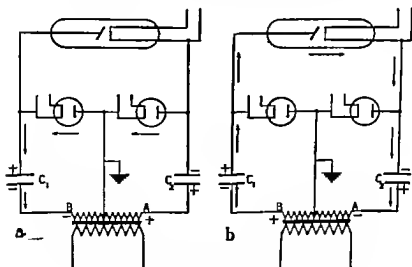


FIG. 87 The Villard circuit by means of which an intermittent potential twice that developed in the transformer is applied to the x-ray tube.

77 The Villard Circuit. — This circuit, also widely used, is illustrated by Figs. 87 and 88. By means of it double the transformer voltage is applied to the tube, but the tube current is not continuous as in the Greinacher arrangement. As will be seen by a study of Fig. 87a, during the half-cycle when A is positive and B negative, current can pass through the valves, the condensers consequently being charged as indicated. On the reverse half-cycle as shown in Fig. 87b current cannot pass through the valves, but each condenser can discharge through the tube, while at the same time, the voltage developed in the secondary of the transformer is also in the right direction to cause a tube current. Since the two condensers, the secondary of the transformer and the tube are all in series, as can be seen in Fig. 87b or Fig. 88 the resultant voltage causing a tube current is equal to the sum of the transformer voltage plus that across C_1 plus that across C_2 .

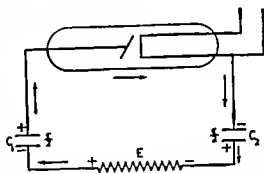


FIG. 88. A portion of the Villard circuit illustrating the half-cycle in which both condensers and secondary of transformer cause a tube current.

Now in a simple circuit such as shown in Fig. 89 where two condensers of equal capacity are joined in series with a battery the voltage drop across each condenser is just one half the E.M.F. of the battery. In Fig. 87a, when the current is passing through the two valves with the condensers in series, we have essentially the same circuit, the secondary of the transformer replacing the battery. The condensers, therefore, are each charged to a voltage of $V/2$ where V is the effective voltage developed by the transformer. Hence, in Fig. 87b, the effective voltage applied to the tube is $V + V/2 + V/2$ or $2V$. Figure 90 taken from valve literature by the Philips Metalix Company is an actual oscillographic record showing

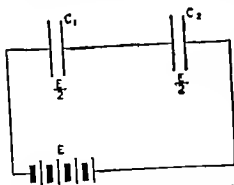


FIG. 89. When two condensers are in series with battery of E.M.F. volts, the potential difference across each condenser is $E/2$ volts.

the changes in tube current in a Villard circuit.

It will be noted that two valves are used in the above arrangement. Actually this is not necessary and in the original circuit, only one was used. It was

found, however that by using two valves, with grounding and the balanced arrangement of Fig 87, more satisfactory operation was obtained, and, moreover, the circuit was more suitable for use with shockproof tubes.

We have by no means exhausted the types of rectifying circuits, but, as the aim of this book is to explain principles rather than give exhaustive tech



Courtesy Philips Metals

FIG. 90. An actual oscillogram of tube current when ordinary metallic tube is operated by Villard circuit.

nical details, it is considered that enough has been given to make clear the fundamental ideas. So far, too, we have confined our attention to arrangements and devices used for ordinary diagnostic and moderate voltage therapy circuits. We have still to discuss ultra high voltage arrangements, but, before doing so it is advisable to consider in detail the properties and nature of x rays themselves.

CHAPTER VIII

GENERAL PROPERTIES OF X RAYS

In section 40 it was pointed out that a beam of x rays radiates from the focal spot of an x ray tube. In this chapter we shall discuss some of the important properties of such a beam

78. Photographic Effect. — X rays affect a photographic plate or film, or sensitized paper in much the same way as ordinary light. The speeds of different photographic emulsions vary and, for the same plate, the speed varies with the kind of rays used.

79 Fluorescent Effect. — X rays excite fluorescence in certain substances on which they fall. By fluorescence we mean the emission of visible light which continues as long as the rays strike the substance. As it was the fluorescent property which led to the discovery of x rays by Roentgen, it is of interest to quote a few sentences from a translation of a preliminary communication read by Roentgen on Dec. 28 1895 before the *Physikalisch-medizinischen Gesellschaft* of Würzburg "If the electric discharge from a large Ruhmkorff coil is passed through a Hittorf vacuum tube or through a sufficiently exhausted Lenard, Crookes, or similar tube and if the tube is covered with a fairly close fitting envelope of thin black card, it will be found that a paper screen placed near the apparatus and covered with barium platino-cyanide will become brightly luminous and fluorescent. It is immaterial whether the prepared side or the unprepared side is turned towards the apparatus. The fluorescence is still noticeable at a distance of two metres from the apparatus. It is easy to establish that the cause of the fluorescence proceeds from the discharge tube and from no other part of the electric circuit.

"The first remarkable feature about this phenomenon is that we have here an agent that can pass through a black card envelope which is impervious to the visible and ultra violet rays of the sun or electric arc and that this agent is capable of producing vivid fluorescence. The fluorescence of barium platino-cyanide is not the only recognisable effect of the x rays. Other bodies also fluoresce, as for instance the calcium compounds known as phosphor; also uranium glass, ordinary glass, calc spar, rock salt, etc.

"Photographic dry plates are sensitive to x rays, and this fact is of special importance in many respects. It enables many phenomena to be recorded, thus making it easier to exclude deceptions, and whenever possible I have checked by means of a photographic exposure every more important visual observation on the fluorescent screen"

In radiology two applications of the fluorescent effect of x rays are made (1) in the use of a fluorescent screen for diagnostic purposes and (2) in the use of intensifying screens for shortening exposures when radiographs are being made. There are few people nowadays who are not familiar with the shadow pictures which the roentgenologist so often studies when a patient is between the x ray tube and the fluorescent screen. Intensifying screens, which are made of such substances as tungstate of calcium are placed directly in contact with the sensitive emulsion on the photographic plate or film. Wherever the rays strike the screen, therefore the bluish (fluorescent) light emitted (which is much more actinic than x rays) acts on the emulsion and so shortens the exposure to a marked degree. A reduction as much as five- to tenfold is quite normal. Care must be taken to keep the screen clean, for particles of dust will absorb the visible fluorescent light and spot the plate. The exposure may be still further shortened by using films sensitized on both sides along with intensifying screens on each side of the film. "In actual use intensifying screens are mounted in rigid holders called cassettes, in order that perfect contact may be obtained between emulsion and screen" (Eastman Kodak Co.)

80 Chemical and Dehydrating Effects. — X rays produce a discoloration of certain alkaline salts, liberate iodine from a solution of iodoform in chloroform and change the color of certain substances such as barium platinocyanide.

81 Biological Effects. — The burns which result from undue exposure of the skin to x rays; the beneficial effects of the rays in curing certain skin diseases; the stunting of the growth of young animals; the production of injuries and of genetic changes in cells; the creation of new species of plants — these are only a few of the many examples of this important property concerning which more will be stated later

82. Ionization Effect. — X rays make the air through which they pass conducting, as may readily be shown by placing a charged electroscope almost anywhere near a tube. On sending a current through the tube it is at once observed that the leaf of the electroscope steadily falls until the whole charge

has disappeared. The rays have ionized the air in the neighborhood of the electroscope to an extent which is proportional to the rate at which the leaf falls. Should the experiment be repeated a number of times, each time placing the electroscope at a greater distance from the tube it would be found that the leaf falls more slowly the further it is removed from the tube. This indicates that the ionization and so the intensity of the beam of x rays at a local region is greater the nearer the region is to the tube (Section 132)

As the ionization property is the basis of the most accurate methods of

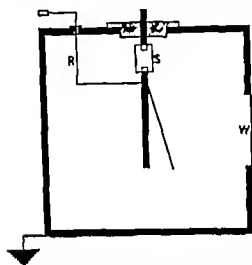


FIG. 91. A simple electroscope for rough ionization measurements.

estimating dosage when x rays are used for treatment, the importance of this property cannot be too strongly emphasized. Later details of suitable ionization chambers will be given; at this place, however a simple form of electroscope which has been found useful may be noted (Fig 91) The leaf is attached to the usual metal support but this, instead of ending in a knob outside the electroscope is supported by means of the insulating bead of sulphur S. The whole is enclosed in an earthed metal chamber with a window W covered with very thin metal foil through which x rays may pass. The electro-

scope is charged by means of a movable rod R which passes through an insulating support to the outside of the box.

83 Penetrating Effect. — There are few people nowadays who are not familiar with the fact that x rays pass through fairly thick sheets of matter which we ordinarily call opaque. A piece of wood is almost as transparent to x rays as window glass is to sunlight. But thin layers of any substance are more transparent than thick, and some substances are more opaque than others; herein lies the basis of the familiar x ray pictures. Radiographs are just shadow pictures, wherein detail is visible because of the unequal degree to which different parts of the subject photographed absorb x rays. There are in consequence corresponding differences in density on the plate or film. As the whole application of x rays both for radiography and for treatment is bound up with the question of absorption of x rays, the question of penetrating power will now be considered in detail.

It is first of all important to realize that the terms opacity, or opaqueness,

or transparency, of a substance to x rays are very indefinite. An experimental illustration will make the point clearer. Before the window of a charged electroscope of the kind shown in Fig 91 is hung a sheet of aluminum several millimeters thick. On placing a small gas x ray tube (operated by an induction coil developing some 10 000 or 20,000 volts) a short distance away with its target pointing towards the window of the electroscope, it is found that the leaf of the electroscope remains stationary or falls extremely slowly. On using a larger tube, however, operated by an x ray transformer on some 50,000 volts, the leaf falls in a matter of a few seconds. The aluminum is opaque to the first beam of x rays, but far from it to the second. In other words, x rays from some tubes are more penetrating than from others.

Again, the same bulb when operated under different conditions emits rays which have different penetrating effects. Suppose a hot filament tube is used, with always the same milliamperage, but at a series of different voltages. Suppose further, that for each voltage the distance of the tube from the electroscope is adjusted so that in each case the leaf falls at the same rate, when no absorbing sheet of metal is present. If now another set of readings is taken from each voltage, at corresponding distances, with an absorbing layer of metal interposed it is found that the higher the voltage the more rapidly the leaf falls. The conclusion is obvious — the higher the voltage across a tube the more penetrating are the rays emitted.

There are, therefore, different kinds of x rays which we may describe as *hard*, *medium* or *soft* according as they are very penetrating, moderately penetrating or feebly penetrating. It will be recalled (section 51) that the same terms are used to describe the state of a gas tube, a hard tube being one for which a higher voltage is required to maintain a certain current than for a soft one. But there is no confusion of terms, for we have just seen that a higher voltage across a tube means an increase in the penetrating power of the rays emitted. A hard tube, therefore, emits an excess of hard rays, a soft tube an excess of soft rays. But the terms hard, medium, and soft, are much too elastic for the accurate measurement of so important a quantity as the penetrating power and we must seek some means of expressing degrees of hardness by definite numbers. In other words, we need a scale in terms of which the quality of a beam of x rays may be expressed.

84 Quality and Tube Voltage. — Since the penetration increases with the potential difference across a tube, any device, such as a spark-gap meter or calibrated primary voltmeter which measures the magnitude of this quantity provides one means of estimating the penetrating power of the rays leaving the tube. (See section 103) A number of years ago, the *Bauer Quality*

After an instrument for measuring quality was on the market. This was essentially an electrostatic voltmeter which indicated the tube voltage by means of a pointer moving over a scale marked with numbers reading up to 10. No. 1 on this scale corresponded to a very low voltage and to rays which were completely absorbed by 0.1 mm of lead and so on until No. 10 indicated rays so penetrating that 1 mm of lead was required for their complete absorption. Quality was then expressed in terms of these arbitrary numbers. Such an instrument is not now used and it is mentioned solely to indicate an early attempt to establish a scale of quality.

No matter how exact the device for measuring tube potentials this information in itself important as it is, is not sufficient to describe accurately the quality of the beam of rays actually utilized. This is true for several reasons. (1) As we shall see presently there is always a mixture of different kinds of rays leaving a target. (2) Two tubes with exactly the same voltage do not necessarily emit rays of exactly the same degrees of penetration. (3) The hardness of what are called characteristic rays (to be discussed later) does not increase steadily with applied voltage. (4) Layers of absorbing material are commonly placed between the tube and the place where the rays are desired, and these *filters* as they are called, alter the average quality of the rays. More direct means of measuring quality are therefore desirable.

In spite of the fact that a knowledge of the magnitude of the peak voltage across a tube does not give sufficient information to describe quality completely in actual practice it is always desirable to give the value of this quantity. In this connection L. S. Taylor gives the following rough classification of the quality of composite beams.

Ultra-soft (Grenz)	5 to 10 Kv
Soft (for diagnosis and superficial therapy)	20 to 120 Kv
Hard (for deep therapy)	120 to 250 Kv
Extra-hard or super-hard, greater than	250 Kv

85 Quality and Half Value-Layer (H.V.L.) — One of the most useful practical means of expressing the quality of a beam of x-rays consists in giving the *half-value-layer* that is, the thickness of some standard substance copper for example necessary to reduce the intensity of the beam by 50 per cent. Obviously the more penetrating the beam, the greater the necessary thickness. This method it will be noticed deals with the absorption of x-rays by matter a very important question which, at this stage, we shall discuss only in its simpler aspects. (See Chapter XI)

Suppose an electroscope *E* Fig. 92 (or any other of the devices for measuring ionization to be considered later), is placed in the path of a beam of

or transparency, of a substance to x rays are very indefinite. An experimental illustration will make the point clearer. Before the window of a charged electroscope of the kind shown in Fig 91 is hung a sheet of aluminum several millimeters thick. On placing a small gas x ray tube (operated by an induction coil developing some 10,000 or 20,000 volts) a short distance away with its target pointing towards the window of the electroscope, it is found that the leaf of the electroscope remains stationary or falls extremely slowly. On using a larger tube, however, operated by an x ray transformer on some 50,000 volts, the leaf falls in a matter of a few seconds. The aluminum is opaque to the first beam of x rays, but far from it to the second. In other words, x rays from some tubes are more penetrating than from others.

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much value nor generally used unless the beam of x rays has been filtered *before* any absorption measurements are made so that the softer components have been almost completely removed. The H V L is then a good general guide to the average penetration of the remainder of the beam although even

TABLE XII — ABSORPTION OF AN X RAY BEAM BY COPPER

Thickness of Cu, in mm.	Intensity
0	100
0.25	63.3
0.5	48.1
0.75	39.3
1.0	30.45
1.25	26.9
1.50	23.0
1.75	20.6
2.00	18.3

then its exact value will depend on the amount of the original filtration. The point is well illustrated by Table XIII which gives some actual observations made by *Bouwers and Van der Tuuk* on the very penetrating rays leaving a tube operated on four different high voltages.

TABLE XIII — HALF VALUE LAYER

Kilovolts	Filtration 6 mm. Cu.	Filtration 15 mm. Cu.
400	5.1 mm. Cu.	5.7 mm. Cu.
500	5.4	5.8
550	5.8	6.1
600	6.1	6.4

Note two things. (1) With the same filtration but increasing voltage, the rays are more and more penetrating as shown by the steady increase in the H V L in either the second or the third column. (2) After increased filtration, in this case 15 mm. of copper as against 6 mm., the beam for any particular voltage is more penetrating. In the third column, the magnitudes of the H V L are all consistently somewhat higher than those in the second for the same voltage.

Because of the wide range in the penetrating powers of different kinds of x rays, the same substance is not suitable for expressing H V L. over the whole range. Soft rays, for example are so readily absorbed by copper that extremely thin sheets would be necessary in making the observations required to determine an H V L. Aluminum is therefore often used as the standard

x rays, and that ionization readings are taken when successive increasing thicknesses of a material like copper are placed at L in the path of the rays. Results such as those given in Table XII, an actual set taken by Dr T G Stoddard, are obtained. These are plotted in graph 1, Fig 93.

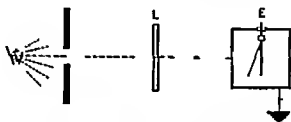


FIG 92. A simple arrangement for examining absorption of a beam of x-rays by an absorbing layer L .

From this graph, it can at once be seen that the thickness of copper necessary to reduce the intensity of the beam from 100 to 50 units, that is, a first 50 per cent is about 0.46 mm.

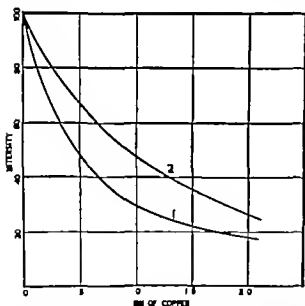


FIG. 93. Absorption of a beam of x-rays by increasing thicknesses of copper. In Graph 1 intensity is plotted against thickness, in Graph 2 the logarithm of the intensity.

If however, we attempt to describe the quality of this beam by stating that the H.V.L. is 0.46 mm. we encounter a difficulty. The same graph shows that the additional thickness necessary to reduce the intensity a second 50 per cent, that is, from 50 to 25 units, is not 0.46 mm. but more than 0.8 mm. Evidently the penetrating power of the rays which got through the first 0.46 mm. of copper has increased. The conclusion is obvious—the original beam must have contained a mixture of rays, some more penetrating than others. The first absorbing layers, therefore removed a greater percent

age of the softer less penetrating rays, thus transmitting a beam with an excess of harder rays.

It may well be asked. What, then, is the use of describing quality by H.V.L. if, when you work with a beam in the way we have just considered, you do not always get the same result? The answer is that the H.V.L. is not of

(1) To reduce the intensity from 100 to 50 units, or from 50 to 25 requires the same thickness of copper *namely* about 0.86 mm

(2) If we consider the increase in absorption brought about by the addition of the same thickness, for example, by 0.25 mm. of copper, the reduction in intensity is always the same *fractional* amount, whether 0.5 mm. is increased to 0.75 or 0.75 to 1.00 or 1.00 to 1.25 etc. Thus, reading off the graph we find that the first 0.25 mm. reduces the intensity from 100 to 81.7 units or about 18 per cent. the second 0.25 mm. from 81.7 to 66.8 or again about 18 per cent. or the third 0.25 mm. from 66.8 to 54.7 once more about 18 per cent.

(3) If the logarithm of the intensity is plotted instead of the actual intensity, the straight line shown in graph 2 of Fig. 94 is obtained. This indicates that when absorption follows the exponential law the log of the intensity decreases by equal amounts (not equal fractions) for equal changes in the thickness of the absorber. The same result is shown by the numbers in the fourth column of Table XIV. If then we wish to test whether a curve is exponential or not, a simple way is to plot the log of the varying quantity, not the quantity itself. If a straight line is obtained, the law is exponential. By way of contrast note graph 1 of Fig. 93. Although this is a plot of the log of the intensity of the beam against the thickness of absorber graph 2 is not a straight line because the absorption of the beam which is not homogeneous, did not follow the exponential law.

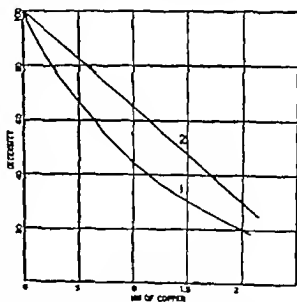


FIG. 94. Graphs showing the absorption of a homogeneous beam of x-rays. In Graph 1 intensity is plotted against thickness, in Graph 2 the logarithm of the intensity.

87 Protection.—Before discussing in detail the most exact method of measuring the quality of a beam of x-rays (by analyzing it into constituent wave lengths) we may here conveniently make further reference to the question of protection. It will be recalled that, in section 62 certain facts were given about protecting an x-ray tube so that, if possible, no rays leave the tube except in the direction in which they are wanted. But even if a

substance for soft rays (20 to 120 Kv) and for the ultra-soft region (5 to 20 Kv) celluloid may be used. For hard rays (120 to 250 Kv) copper is the usual substance, while for the super hard region, tin has been suggested for 250 to 600 Kv, and lead above 600 Kv.

86. Homogeneous Beam and Exponential Law — In Chapter X we shall learn that it is possible to separate a beam of x rays into monochromatic components just as a beam of ordinary light is broken up into its constituent wave lengths. When a *monochromatic* beam of x rays is examined for absorption in the above manner it is found that *no matter what the amount of the original filtration*, equal thicknesses of the absorbing material reduce the intensity of the beam by the same fraction; or, in other words, that the H V L remains constant whether the intensity is reduced from 100 to 50 units, or from 50 to 25, or from 25 to 12.5.

Whenever the magnitude of any quantity changes according to such a law; that is, whenever, in the case of x rays, for each successive equal thickness of absorbing material, the intensity decreases by the same fraction the change follows the *exponential law*. Or, to take an example from radioactivity whenever for each successive interval of time the intensity of the rays from radium decreases by the same fraction the change is exponential. As this law is of great importance in radiology the student should try to understand it clearly.

TABLE XIV — AN EXAMPLE ILLUSTRATING ABSORPTION OF A BEAM ACCORDING TO THE EXPONENTIAL LAW

Thickness of Absorber	Intensity	Logarithm of Intensity	Difference in Successive Logarithms
0	100	2.000	
0.25 mm.	81.7	1.912	0.088
0.50	66.8	1.825	0.087
0.75	54.7	1.738	0.087
1.00	44.7	1.650	0.088
1.25	36.5	1.562	0.088
1.50	29.9	1.475	0.087
1.75	24.5	1.389	0.086
2.00	20.0	1.300	0.089

In Fig. 94 the curved line, which is a plot of the results given in the first two columns of Table XIV follows the exponential law that is, it is applicable to the absorption of a pure homogeneous beam of x rays by successive thicknesses of an absorbing material such as copper. Study it carefully and note the following three things.

(1) To reduce the intensity from 100 to 50 units, or from 50 to 25 requires the same thickness of copper, namely, about 0.86 mm.

(2) If we consider the increase in absorption brought about by the addition of the same thickness, for example, by 0.25 mm of copper, the reduction in intensity is always the same *fractional* amount, whether 0.5 mm is increased to 0.75 or 0.75 to 1.00 or 1.00 to 1.25 etc. Thus, reading off the graph, we find that the first 0.25 mm reduces the intensity from 100 to 81.7 units or about 18 per cent the second 0.25 mm, from 81.7 to 66.8, or again about 18 per cent or the third 0.25 mm from 66.8 to 54.7, once more about 18 per cent.

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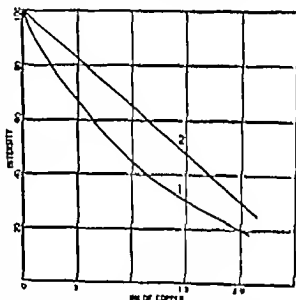


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87 Protection. — Before discussing in detail the most exact method of measuring the quality of a beam of x rays (by analyzing it into constituent wave lengths), we may here conveniently make further reference to the question of protection. It will be recalled that, in section 62 certain facts were given about protecting an x ray tube so that, if possible, no rays leave the tube except in the direction in which they are wanted. But even if a

tube is adequately protected in this way, protection must be provided from the direct beam itself. If sufficiently penetrating, this beam may easily pass through the walls of the tube room, causing injury to people in an adjoining room who may be completely unaware of its presence. In the diagnostic or treatment room itself, great care must be exercised by those actually using the beam. In screening, for example, where diagnosis is made by visual observation of the shadow picture on a fluorescent screen, the diagnostician who is in the direct path of the rays, must be protected. This is accomplished to a considerable extent by covering the screen with transparent lead glass of sufficient thickness to absorb most of the rays which strike the screen.

Again, just as a beam of ordinary light is scattered by fine dust particles in the air, so a beam of x rays, on striking matter, may be scattered in all directions and be radiated to places far removed from the direct path of the rays. (See Chapter XI)

So important is the question of adequate protection that the International Congress of Radiology has drawn up certain recommendations. These are printed in an appendix at the end of this book. At this stage, we direct attention to the following

(1) Since in the beam which leaves a tube there is always a mixture of soft and hard rays, it is generally necessary to remove the softer components

TABLE XV — EQUIVALENT LEAD THICKNESS FOR ADEQUATE PROTECTION

Peak Voltage	Minimum Lead Equivalent
75 kv	1.0 mm.
100	1.5
125	2.0
150	2.5
175	3.0
200	4.0
250	6.0
300	9.0
350	12.0
400	15.0

by filters. For example, suppose a deep-seated tumor is being treated by rays which, of necessity, must be fairly penetrating. If the soft rays were not removed by filtration they would be absorbed by the skin and intervening tissue, with consequent danger of serious injury.

(2) We have already emphasized that the higher the tube voltage, the greater the average penetration of the x ray beam. Suitable protection against 50 000 volts rays will not then be adequate for 200 000 volts. Consequently

protection rules specify the necessary minimum thickness of absorbing material for a range of voltages. Because of its great density and availability lead is more or less taken as a standard substance in specifying suitable thicknesses of absorbing material (see however, section 120). Thus, in Table XV taken from the Recommendations of the British X Ray and Radium Protection Committee, the numbers in the second column give the minimum equivalent thicknesses of lead for adequate protection against rays generated by the peak voltages in column one.

TABLE XVI—EQUIVALENT THICKNESSES OF LEAD FOR IRON

Lead Equivalent	Equivalent Thickness of Iron				
	150 Kv	200 kv	300 kv	400 kv	radium gamma rays
1 mm.	11 mm.	12 mm.	12 mm.	11 mm.	2.5
2	25	27	20	18	5
3	37	40	28	23	7
4	50	55	35	28	8.5

If lead itself is used, these are the actual thicknesses required. If, however some other material is to be used, then by actual experiment, the equivalent lead thickness must be found. For example in Table XVI and Table XVII will be found equivalent lead thicknesses of iron and of concrete (2 parts ballast, 2 parts sand, 1 part cement) as found by the National Physical Laboratory, England.

TABLE XVII—EQUIVALENT THICKNESSES OF LEAD FOR CONCRETE

Lead Equivalent	Equivalent Thickness of Concrete				
	150 Kv	200 Kv	300 kv	400 kv	radium gamma rays
1	85	80	60	50	3
2	160	150	95	75	16
3	230	210	125	100	22
4	295	275	150	120	28

Thus, when using x rays generated at 200 Kv the equivalent of 4 mm of lead is obtained by 5.5 cm. of iron or 27.5 cm. of this kind of concrete. It is interesting to note that at the highest voltages given in the tables, both iron and concrete, *relatively to lead* become better absorbers.

CHAPTER IX

ELECTROMAGNETIC WAVES

For many years after their discovery by Roentgen in 1895, the exact nature of x rays was a subject about which there was much speculation. Although Roentgen himself thought of the new rays as a wave phenomenon it was not until 1912 that conclusive evidence concerning their nature was given. In that year, however, as a result of the work of Laue, assisted by Friedrich and Knipping, it was experimentally demonstrated that the phenomenon of interference could be obtained with x rays, and that consequently they were without doubt a form of wave motion. The pioneer work of these men at

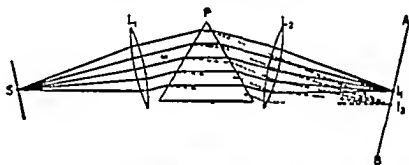


FIG. 95 The optical arrangement in a prism spectrograph.

once led to methods of measuring the constituent wave lengths of a beam of x rays. Before discussing this question in detail, it is desirable to give a brief review of electromagnetic waves, with particular reference to those of biological importance.

88. The Spectrograph.—The student will recall the familiar facts about the visible spectrum. When a beam of white light passes through a prism, a spectrum ranging from red to violet is formed, because red light is deviated by the prism less than yellow, yellow less than green, green less than blue, and blue less than violet. A common arrangement for obtaining a focused spectrum on a screen or photographic plate is shown in Fig. 95 where *S* represents a narrow slit illuminated by the light source to be examined and *L*₁ is a collimating lens placed at its focal distance from the slit so that a beam of parallel rays emerges and falls on the prism, *P*. The light emerging from

the prism is collected by the lens L_2 and focused on the screen or plate AB . Since each kind of light is deviated a different amount by the prism there are as many emergent bundles of light as there are kinds in the original beam and hence a corresponding number of focused images on the screen. In the figure I_1 and I_2 there are two such images.

When a photographic plate is used permanent records, such as illustrated in Fig. 96 and Fig. 97 are obtained the whole arrangement constituting a

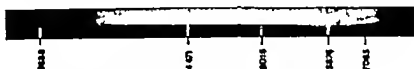


FIG. 96. The continuous spectrum emitted by an incandescent lamp or any white hot solid, with helium spectrum superimposed.

spectrograph. If the source of light is an incandescent lamp there are so many constituent wave lengths that the images overlap giving a continuous spectrum such as Fig 96. Many sources, however, such as luminous hydro-

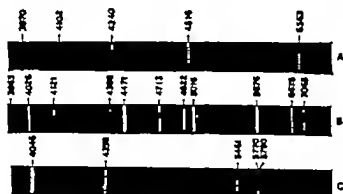


FIG. 97 Line spectra in the visible region, emitted by a, hydrogen, b, helium, and c, mercury vapor

gen or mercury vapor emit only isolated wave lengths, giving spectra like Fig 97 where each spectral line corresponds to a definite wave length.

89 Measurement of Wave Length.—The determination of the actual wave lengths of these spectral lines is an important practical problem. Every method is based on the principle of interference that is, the principle that when two (or more) light beams are superimposed the resultant may be either light or darkness, depending on the phase difference between the

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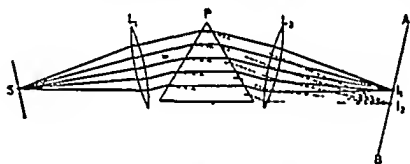


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Suppose now that at a value of $\theta = \theta_1$ the path difference between successive rays is exactly one wave length that is, that $s \sin \theta_1 = \lambda$. Then the rays for this particular direction when superimposed all arrive in step or in phase, reinforcing each other, and a very bright image results. Other bright images

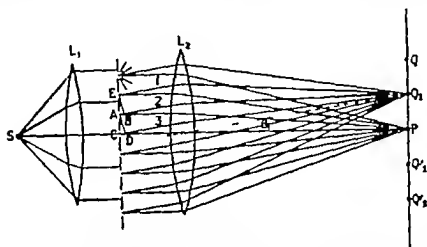


FIG. 99 Optical arrangement for obtaining a spectrum with a transmission grating.

are obtained in the special directions $\theta_1, \theta_2, \theta_3$ etc., where $s \sin \theta_1 = 2\lambda$; $s \sin \theta_2 = 3\lambda$; $s \sin \theta_3 = 4\lambda$ etc. With the arrangement shown in Fig 99 then the original beam of monochromatic light gives rise to a central bright image or order at P (where the rays reinforce because the path difference between any two is zero and again all are in step) first order images on either side of P at Q_1 and Q_2 corresponding to the angle θ_1 second order images at Q_3 and Q_4 corresponding to θ_2 , and possibly higher orders.

If the original beam instead of being monochromatic, consists of a mixture of wave lengths, we obtain a series of first order images, one for each constituent wave length, and another series of second order images or the light is spread out into a first and second order spectrum (and possibly higher orders) If for each image in a spectrum we measure the corresponding θ and θ_2 (as we can readily do by means of a spectrometer) then the wave lengths can at once be found, from either of the relations

$$\lambda = s \sin \theta_1 \quad \text{or} \quad 2\lambda = s \sin \theta_2,$$

provided that the magnitude of s is known

Instead of a transmission grating a reflection grating is often used. A

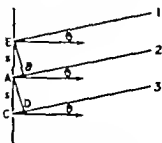


FIG. 100. Enlargement of a portion of Fig. 99

disturbances. If two beams are exactly in step, crest meeting crest, trough meeting trough, there is a resultant maximum disturbance, or brightness; if the two are exactly out of step, crest of one meeting trough of the other, there is darkness. One such method for evaluating wave lengths, which the student is asked to recall because of its connection with x ray work, makes use of the diffraction grating.

If water waves strike a barrier with an opening such as *M*, Fig 98*a*, which is small in comparison with the wave length of the waves, the disturbance spreads out from the opening in all directions. Similarly, if a beam of monochromatic light strikes a narrow opening, of width say $\frac{1}{1000}$ mm., as in

Fig 98*b*, the light too spreads out (or is diffracted) over a wide angle. Now

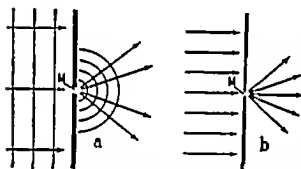


FIG. 98. When plane waves or parallel rays strike an obstacle with an aperture of width comparable with the wave length, the wave disturbance spreads out from the aperture.

consider a surface on which there is a large number of small openings, spaced at regular intervals, as in a transmission grating. If a beam of parallel rays of monochromatic light is incident on such a grating, somewhat as shown in Fig 99 light spreads out from each opening. If this diffracted light falls on a lens L_2 , at every point in its focal plane there will be a superposition of as many little bundles as there are openings in

the grating. Figure 99* shows the superposition at P and at Q_1 of the bundles in two directions.

It is important to note that since the rays which are superimposed at any one point are all incident on lens L_2 in the same direction, the path difference, that is, the distance one ray travels farther than its neighbor is the same for each successive pair of rays. Thus, using Fig 99 or the enlargement in Fig 100, ray 2 travels a path from the grating to Q_1 which is greater than the path for ray 1 by AB ; ray 3 a path greater than ray 2 by $CD = AB$, and so on for every successive pair. Moreover the actual magnitude of this path difference is easily seen to be $s \sin \theta$ where s is the *grating element*, that is, the distance EA or AC from one opening to the next; and θ is the angular distance of the point Q_1 from the original direction of the beam of light. This path difference, then, steadily increases, the greater the angle θ .

* Although in an actual grating there may be several thousand small openings, in this figure only a few are shown, in order to make clear the underlying ideas.

91 The Infrared. — The student will recall that the spectrum does not end with the region where the eye ceases to have the sensation of red. Beyond the visible red is an invisible region of longer wave lengths, called the *infrared*, a region which may readily be made evident by the rise in temperature of a sensitive instrument such as a thermopile or radiometer or even the blackened bulb of a thermometer. Infrared rays are sometimes called heat rays because of this development of heat when they are absorbed, but the name is misleading since the energy of visible and other electromagnetic waves on absorption is also changed into heat.

At least part of the infrared region may be examined photographically because in recent years, emulsions have been developed which are sensitive to part of this region. Figure 102 for example, is a photograph of the spectrum

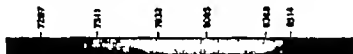


FIG. 102. Spectrum in the near infrared.

of the iron are showing wave lengths extending beyond 8500 angstroms. Apart altogether from spectrum work, infrared photography has important applications, although most of them are not of special interest to the medical student. Many of the applications arise from the fact that infrared rays, because of their longer wave lengths, are less scattered by fine particles of dust or fog in the atmosphere and so are much more penetrating. Details of distant landscapes, for example, stand out with remarkable clearness. Indeed, mountain ranges have been photographed at a distance of several hundred miles; and from airplanes well over four miles high infrared photographs showing details over a wide range of terrain are taken.

92. Infrared Radiation in Medicine. — Whether or not infrared radiation has any specific value in medicine, the writer of this book is not prepared to say. One thing, however is certain. The longer wave lengths in the near infrared can penetrate superficial tissue more readily than visible or ultraviolet radiation and so readily cause a rise in temperature on absorption. Specific claims of the value of infrared radiation should be carefully examined because any beneficial effect may be due largely or entirely to temperature.

93 Electric Waves. — In Chapter XVI certain details about rapidly oscillating electric currents will be given. Such oscillations generate electro-

good reflection grating is made by ruling, with a diamond point and a dividing engine, a series of regularly spaced grooves on polished speculum metal. If such a grating is made on a plane surface and a beam is incident as in Fig. 101, the light is diffracted and bundles of rays in the same direction are superimposed by a lens at Q as with the transmission grating. For exactly the same reason as given above, spectra are obtained, and a complex beam is analyzed into its constituents. In another very important type of reflection grating, rulings are made on a concave surface. With this type, it is possible to obtain superimposed bundles without the use of a lens.

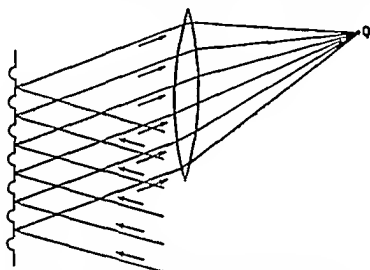


FIG. 101 To illustrate the principle of a plane reflection grating.

90 The Angstrom and Millimicron. — Measurements obtained with gratings (and other means) show that the visible spectrum contains wave lengths ranging from about 0.00004 cm. at the violet end to slightly greater than 0.00007 cm. at the red end. When isolated wave lengths emitted by different substances are measured, we obtain such values as 0.00007682 for a potassium red line, 0.00006563 for a hydrogen red line, 0.00005790 and 0.00005770 for two bright mercury yellow lines, 0.00005461 cm. for a very bright mercury green and so on for literally tens of thousands of measured lines. Since these wave lengths are so very small, for convenience, instead of using a centimeter as unit of length the *angstrom* and the *millimicron* are often used. An angstrom (called after Angstrom, a Swedish pioneer in spectroscopy) is equal to 10^{-8} cm. A micron being equal to $\frac{1}{1000}$ mm., a millimicron is $\frac{1}{1000}$ of a micron or 10^{-4} mm., or 10^{-7} cm. The above wave lengths may then be written in angstroms as 7682 6563, 5790 5770 5461 and in millimicrons or $m\mu$ as 656.3 579.0 577.0 546.1

95 Sources of Ultraviolet. — Attention is directed to the following sources of special interest to medical students.

(a) An arc or other electric discharge through mercury vapor. With such a source the spectrum of Fig. 104 was taken. Note that the radiation is confined largely to isolated wave lengths, some of which are much more intense than others.

(b) Any open arc, such as that between the carbon poles of a projection lantern or between any two metal rods.

(c) *The Sun.* Under the most favorable conditions, such as high noon in midsummer the shortest wave length in the solar spectrum is in the neighborhood of 2950. Ordinary window glass, as we have already noted will transmit nothing shorter than about 3200.

According to figures given by F. S. Brackett of the Smithsonian Institute, of the total solar energy radiated, from 1 to 5 per cent is in the ultraviolet, from 41 to 45 per cent in the visible and from 50 to 58 per cent in the infrared.

The amount of indirect radiation from the sky as distinguished from the direct rays of sunshine, depends on the wave length but for the region 2900–3200 it may exceed that of the direct beam.

(d) *Sun Lamps.* If an incandescent lamp is to be used as a sun substitute for ultraviolet, the bulb must be made of glass transparent to at least 3000 angstroms, and the luminous source must radiate wave lengths as short as this limit. Two different means have been used to fulfill the second condition

(i) Lamps such as Mazda S-1 and S-2 contain mercury so that when in operation there is an arc between tungsten terminals, in an atmosphere of

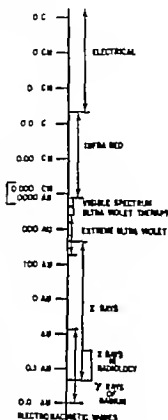


FIG. 103. Schematic representation of complete range of electromagnetic wave.



FIG. 104. The near ultraviolet spectrum of mercury vapor

mercury vapor. The resulting spectrum is a combination of a continuous band in the red and green region plus characteristic mercury vapor lines as far as the strong line 2967 (see Figs. 104 and 105). (u) By constructing

magnetic waves as Hertz first showed in 1887. The work of Hertz, which experimentally confirmed the predictions of Maxwell, put on a firm basis the electromagnetic theory of light, and was the real beginning of wireless telegraphy. Light waves and waves generated electrically are of exactly the same nature. Many of their properties, it is true, are different. Thus some electric waves pass readily through a brick wall, whereas visible light waves do not. But, in spite of differences in properties which arise from differences in wave length, the essential nature of electric waves, light waves, and all the others considered in this chapter is exactly the same. They are all electromagnetic periodic disturbances traveling in free space at a speed of 186,000 miles or 3×10^{10} cm per second. (See section 197.)

As will be seen in Table XVIII, the longest infrared waves are shorter than the shortest waves generated electrically. On the other hand electric waves may be several miles in length.

TABLE XVIII — RANGE OF ELECTROMAGNETIC WAVE LENGTHS

Electric and Hertzian	20+ miles	to 0.22 mm.
Infrared	0.4 mm.	to 0.0007 mm.
Visible Light	0.0007 mm. or 7000 Å	to 0.0004 mm. to 4000 Å
Ultraviolet and Extreme ultraviolet	4000 Å	to 40 Å
X-rays	500 Å	to 0.06 Å
X-rays in radiology	1.0 Å (approx.)	to 0.06 Å
Gamma	0.3 Å	to 0.006 Å

Figure 103 depicts the range of electromagnetic waves in schematic form.

94 The Ultraviolet. — Beyond the violet end of the visible spectrum, another invisible region, the *ultraviolet*, is readily revealed either by photography or by means of the fluorescent light emitted when ultraviolet rays fall on certain substances. Figure 104 is a photograph of the spectrum of mercury vapor in which the wave lengths of most of the spectral lines are in the ultraviolet region. Since ordinary glass completely absorbs wave lengths shorter than about 3200 angstroms (see Fig. 105) a spectrograph for the analysis of the ultraviolet must use prisms and lenses of some other material. By far the commonest is quartz, which is transparent to wave lengths as short as 1850. The use of fluorite extends the limit to about 1200 and of lithium fluoride to about 1083. In this region absorption difficulties become very great. Air itself at atmospheric pressure is too opaque for the investigation of wave lengths in the extreme ultraviolet, and vacuum spectrographs, with concave gratings, become necessary. With this type of instrument wave lengths as short as 40 angstroms have been photographed.

To examine the effect quantitatively first of all some biological reaction must be agreed on as a standard, or as near a standard as is possible in biological work where individuals differ so much. The standard effect commonly adopted is the *minimum perceptible erythema* or the M.P.E., which may be defined as a "barely perceptible reddening of an average untanned skin." The "dose" necessary to produce an M.P.E. must next be determined. If there were a single constant source of ultraviolet radiation this would involve only a determination of the time necessary to cause an M.P.E. For example, the Mazda S-1 sunlamp, at a distance of 30 inches, produces an M.P.E. in from 5 to 7 minutes. But everybody does not use Mazda S-1 lamps, and even the layman knows that the useful ultraviolet content of the sun varies tremendously with the season of the year. It is therefore necessary to have some means of measuring fundamentally the actual intensity of the ultraviolet component of the radiation which is effective in producing erythema.

Over a wide range of wave lengths, extending from the infrared to well down in the ultraviolet, intensity may be measured by any sensitive detector of the rise in temperature which results from the absorption of radiant energy. For this purpose the thermopile, the thermocouple, the bolometer and the radiometer are all used. In using an instrument like the thermocouple one may either measure the intensity of the beam as a whole, or the beam may be separated into its constituent wave length and the relative intensities measured by moving the thermocouple along the spectrum. In the latter case some form of amplification is desirable.

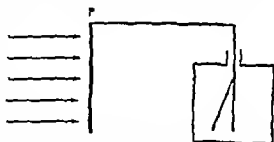


FIG. 106. When light of suitable wave length falls on a zinc plate *P* joined to the insulated part of an electroscope, the electroscope if negatively charged loses its charge.

If the specific problem is an examination of the intensity of the erythema producing rays, the remainder of the rays can be removed by a suitable filter. This is what is effectively done when use is made of the *photoelectric effect*, a phenomenon which may be demonstrated by the following simple experiment. Suppose an insulated zinc plate *P* Fig. 106 is joined to the knob of an electroscope, and that the system is negatively charged. With proper insulation the leaf of the electroscope remains for some time with deflection unchanged. If however light from an arc lamp is allowed to fall on the metal plate the electroscope leaf quickly falls. If the system is positively charged no such discharge takes place. The discharge when the plate is negatively charged is caused by a photoelectric emission of electrons from the surface on

a lamp, such as the Mazda C-4, so that the filament temperature is considerably higher than normal, the emitted radiation extends into the ultraviolet nearly but not quite as far as the solar spectrum.

An ordinary incandescent lamp with tungsten filament is not of much use as a source of ultraviolet even with a quartz envelope, because, although any hot body radiates a continuous spectrum, the region in which maximum energy occurs depends on the temperature, and unless this is higher than the normal operating temperatures of tungsten filaments, there is very little in the ultraviolet. A hot iron ball, when scarcely visible or even invisible in the dark, radiates energy and may readily be photographed in the dark with infrared plates. This is because the region of maximum energy is in the infrared. (Incidentally this is the reason infrared rays are sometimes misleadingly called heat rays.) If the temperature of the iron ball is raised, it becomes red hot, in accordance with the law that the higher the temperature, the shorter

the wave length in the region of maximum radiation. In the solar spectrum, the region of maximum intensity is around 5000 angstroms. As this corresponds to a temperature of about 6000° absolute and in the most powerful incandescent

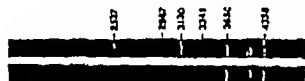


FIG. 105 Spectra of mercury vapor (a) without filter of ordinary window glass; (b) with such a filter.

lamps, maximum temperatures are only about 3350° absolute, we see how difficult it is to reproduce completely the solar spectrum by high temperature.

96. The Use of Ultraviolet in Medicine. — Reference will be made to three ways in which ultraviolet light is of importance to the medical student (1) as an agent for the production of erythema; (2) as an agent for killing bacteria; and (3) as an agent for the manufacture of vitamin D. As always, in this book we are concerned primarily with basic physical ideas.

Few people are unaware of the effect of sunlight on the skin. To examine this effect scientifically some relation must be found between the biological effect — the reddening of the skin followed by tanning — and the intensity and the quality of the radiation. As far as quality goes, examination of the effect of different wave lengths shows that ultraviolet light is necessary for tanning and that, if we restrict ourselves to sunlight, the most effective range is between 2900 and 3100 angstroms. It is, therefore, only the extreme short wave length end of the solar spectrum which is useful; in fact, the useful component is so near this end that during the shortest days of the year the erythema-producing component is negligible.

certain number of these agreed upon as a unit of radiation intensity. Then an intensity of this magnitude delivered for a specified time would constitute a unit of dosage. Although this procedure has not come into general use, it has been followed by special workers in this field. As an example, a brief reference is made to work done by Luckiesh and collaborators at the Lighting Research Laboratory of the General Electric Company. The unit of dosage adopted is the *E-viton hour per sq. cm.* where the E viton per sq. cm. is a unit of intensity defined as 10 microwatts per sq. cm. at 2967 angstroms. Wave length enters into this definition because of the differences in the ability of different wave lengths

to produce an erythema. In order to find the number of microwatts per sq. cm. equal to an E viton for another wave length, use must be made of a curve such as that given in Fig. 108 showing the relative effectiveness of different wave lengths in the production of erythema. Such curves have been obtained by Luckiesh and other workers. Suppose we wish to find the E viton for wave length 3022. We consult

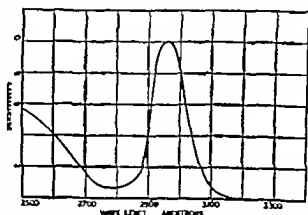


FIG. 108. Curve showing relative effectiveness of different wave lengths in the production of erythema. (After Luckiesh and co-workers.)

the curve reproduced in Fig. 108 noting that when the effectiveness of 2967 is taken as 1 that of 3022 is only 0.55. For this wave length, then the

E viton is $\frac{1.0}{0.55}$ or about 18 microwatts per sq. cm.

Making use of such ideas, General Electric workers have recently (June 1937 and October 1939) published curves showing the number of E viton hours per sq. cm. of erythema producing solar ultraviolet radiation received on a horizontal plane each month for a period of four years. Their results give numbers ranging from as low as 27 for December to 452 for June. It is interesting to note also that the highest intensity recorded during the whole four years period was about 4.20 E vitons per sq. cm. "This, these workers said, will produce an M.P.E. on average untanned skin in about 10 minutes.

By exposing several men to sunlight in the month of July it was found that the average dose necessary to produce an M.P.E. was $\frac{1}{2}$ of an E viton hour per sq. cm.

which the light is incident. A photoelectric cell is a refined device making use of this principle. In one form, a highly evacuated tube *T* (Fig. 107), has an anode consisting of a single wire or ring projecting into the tube, and a cathode, a large area of a metal surface spread over a part of the inside wall. When such a tube is inserted in a circuit, as shown in Fig. 107, and light falls on the metallic surface, a current is indicated by the galvanometer *G* because

of the photoelectric emission of electrons from the surface.

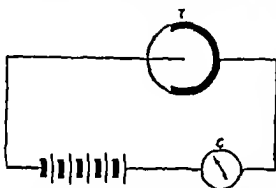


FIG. 107 Simple arrangement of photoelectric cell *T* with galvanometer and battery

In connection with the relation between this current and the nature of the incident light, two important facts should be noted. (1) The magnitude of the photoelectric current is directly proportional to the intensity of the incident light. The galvanometer reading, therefore, is a measure of the intensity of the light. (2) For any given metallic surface, wave

length longer than a certain critical value do not cause any photoelectric emission. For example, if the above experiment is repeated with a piece of red glass in front of the zinc plate the electroscope is not discharged, because for zinc the critical wave length is about 3020 angstroms, and the light transmitted by a piece of red glass includes little shorter than 6000 angstroms.

The value of the critical or threshold wave length depends markedly on the nature of the surface. Thus, for the element caesium it is 6810 angstroms, for sodium 5830 for aluminum 4770 for silver 3250 for cadmium 3140, and finally for an alloy of cadmium and magnesium 3350. For the examination of the intensity of the erythema-production component of solar radiation a photoelectric cell with a cadmium-magnesium surface is particularly useful, because its spectral sensitivity is such that it responds to the ultraviolet energy of various wave lengths approximately in accordance with their effectiveness in producing erythema or sunburn. It should be borne in mind that the region of wave lengths for which a photoelectric surface has a *maximum* sensitivity is somewhat below the critical wave length. For a cadmium-magnesium surface, the greatest sensitivity is around 2800 angstroms. In the production of erythema the most effective wave lengths are in the region 2950 to 3000. Note (see Fig. 104) that in the mercury spectrum a fairly strong line occurs at 2967.

To measure dosage the galvanometer readings must be translated into fundamental units of intensity such as ergs per sq. cm. per second, and a

certain number of these agreed upon as a unit of radiation intensity. Then an intensity of this magnitude delivered for a specified time would constitute a unit of dosage. Although this procedure has not come into general use, it has been followed by special workers in this field. As an example, a brief reference is made to work done by Luckiesh and collaborators at the Lighting Research Laboratory of the General Electric Company. The unit of dosage adopted is the *E-viton hour per sq. cm.* where the E viton per sq. cm. is a unit of intensity defined as 10 microwatts per sq. cm. at 2967 angstroms. Wave length enters into this definition because of the differences in the ability of different wave lengths

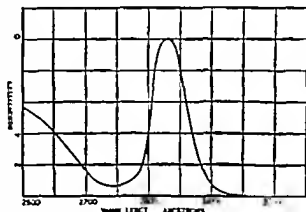


FIG. 108 Curve showing relative effectiveness of different wave lengths in the production of erythema. (After Luckiesh and co-workers.)

to produce an erythema. In order to find the number of microwatts per sq. cm. equal to an E viton for another wave length use must be made of a curve such as that given in Fig 108 showing the relative effectiveness of different wave lengths in the production of erythema. Such curves have been obtained by Luckiesh and other workers. Suppose we wish to find the E viton for wave length 3022. We consult the curve reproduced in Fig 108 noting that when the effectiveness of 2967 is taken as 1 that of 3022 is only 0.55. For this wave length, then the E viton is $\frac{10^7}{0.55}$ or about 18 microwatts per sq. cm.

Making use of such ideas, General Electric workers have recently (June 1937 and October 1939) published curves showing the number of E viton hours per sq. cm. of erythema-producing solar ultraviolet radiation received on a horizontal plane each month for a period of four years. Their results give numbers ranging from as low as 27 for December to 452 for June. It is interesting to note also that the highest intensity recorded during the whole four years period was about 4.20 E vitons per sq. cm. "Thus, these workers said, "will produce an M.P.E. on average untanned skin in about 10 minutes."

By exposing several men to sunlight in the month of July it was found that the average dose necessary to produce an M.P.E. was $\frac{1}{3}$ of an E viton hour per sq. cm.

97 Bactericidal Effect of Ultraviolet. — Certain corporations such as the Westinghouse have on the market small sterilizing lamps with such a low power consumption that they can be used inside a refrigerator. The radiation from these lamps, it is claimed, has a bactericidal effect, preventing the formation of mold, for example. A description of one such lamp states that it consumes 15 watts and that 95 per cent of its radiant energy is emitted as wave length 2537. Note that this wave length, one of the strong spectral lines in the mercury spectrum (see Figs. 104 and 105) is in a region much shorter than that of the erythema-producing rays. Many investigators have shown that the wave lengths in this region have a strong lethal effect for many kinds of bacteria. One investigation for example showed that wave lengths ranging from 2536 to 2225 were much more effective in killing typhoid bacilli than the ultraviolet region near the visible spectrum. Sunlight has undoubtedly a sterilizing effect on some organisms, but the quartz mercury vapor lamp, or any source rich in the emission of radiations in the region 3000 to 2200 is a far more effective agent.

98. Production of Vitamin D — Ultraviolet of selected wave length is of great importance in the production of vitamin D, the organic agent which promotes normal calcium metabolism. The absence of vitamin D from a diet means imperfectly calcified bones. Children whose diet is deficient in vitamin D may develop rickets, and, if they do, they may be cured by irradiation of ultraviolet in the erythema-producing band, 2800 to 3000. The cure is due to the fact that, when the ergosterol in the skin absorbs the wave lengths in this region vitamin D is manufactured and subsequently gets into the blood stream. The ergosterol is said to be activated.

Some foods contain vitamin D. Others, originally lacking it, may be activated by ultraviolet irradiation.

99 X Rays and Gamma Rays. — Our range of short electromagnetic waves is extended still farther by these important kinds of rays. As each of these will be discussed in detail they are mentioned here simply to complete our list. (Note again Fig. 103.)

CHAPTER X

MEASUREMENT OF WAVE LENGTH OF X RAYS

100 Reflection of X Rays. — It has already been stated that the work of von Laue and his colleagues in 1912 proved without any doubt that x rays had a wave nature just like ordinary violet and ultraviolet light. Before that date other experimenters had tried with some success to prove the wave nature of x rays. One of the simplest of the early experiments consisted in examining whether or not there was any spreading out when the rays fell on a narrow aperture (See Fig 98) Although the results of experiments of this kind were not conclusive they did provide evidence that, if x rays had a wave nature, the wave lengths must be of the order of 10^{-8} or 10^{-9} cm. With this evidence in mind, it occurred to von Laue that a crystal whose regular structure was known to have a spacing between atom layers of the order of 10^{-8} cm. might act towards x rays much the same as a diffraction grating acts towards light. The idea was tested by experiment and proved to be one of the most fertile in modern science.

In Laue's original experiment a narrow beam of x rays traversed a zinc blende crystal, and the emergent beam fell on a photographic plate. On development the plate showed a regular pattern of bright spots on a dark background.

In interpreting this result W. L. Bragg of England showed that it was possible to look on cleavage planes of crystals as reflecting surfaces and subsequently in collaboration with his father Sir William Bragg developed a technique which proved of tremendous value for the analysis of an x ray beam as well as for the examination of structure of crystals.

Consider a narrow beam of x rays, represented by AC in Fig 109 incident on the face of a crystal in a direction making an angle θ with this face. The question arises: Is there a reflected beam in the direction CD , as there is if AC represents a beam of light and the crystal face is replaced by a mirror? According to Bragg's ideas, which experiment soon verified many times over

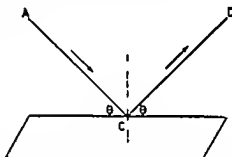


FIG. 109 An x-ray beam along AC under certain conditions is regularly reflected from the face of a crystal along CD .

a cleavage plane of a crystal with its very regular arrangement of atoms, acts as a mirror for x rays, nature providing the smooth surface necessary to reflect regularly waves as short as those of x rays. The reflection of x rays from a crystal, however, differs in one important respect from optical reflection at a mirror. Since x rays penetrate matter there is a series of reflections from successive parallel planes of atoms. The beam CD , therefore, in reality consists of a number of superimposed beams, each reflected from a different plane of the crystal.

Now let us enlarge the scale of our diagram sufficiently to show successive layers, as we have done in Fig 110, for four layers. Then, remembering that

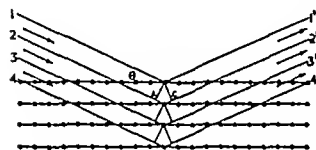


FIG. 110. Reflection of x-rays from successive parallel planes of atoms in a crystal.

the planes are separated distances not much greater than 10^{-8} cm, we see that even a narrow beam like AC when enlarged on the same scale, will, in Fig 110, be represented by several lines such as 1, 2, 3, 4, with corresponding reflected rays 1', 2', 3' 4'. Moreover, it is not difficult to see that the path of the disturbance along

11 is shorter than that along 22' 22' shorter than 33, and so on. For disturbances 11 and 22' this path difference is equal to $AB + BC$ as shown in Fig 110. With a little simple trigonometry, this can readily be shown to be equal to $2d \sin \theta$ where d is the distance between successive layers, and θ is the angle which the beam of rays makes with the face of the crystal. For any successive pairs of disturbances, the path difference will be the same.

We see then that the beam CD of Fig 109, really consists of a superposition of a number of beams, with a path difference between every successive pair equal to $2d \sin \theta$. Just as with a diffraction grating and ordinary light (see section 89) it follows that all the component beams will unite to form a resultant intense beam only if this path difference is equal to one, or two or three or more wave lengths. This means that when a beam of homogeneous x-rays is incident on the face of a crystal, there is a reflected beam of marked intensity only for very special angles of incidence. If the incident beam contains a number of different wave lengths then, for any given angle of incidence there is an intense reflected beam only if there is a component whose wave length λ is such that $\lambda = 2d \sin \theta$ or $2\lambda = 2d \sin \theta$ etc. Analysis of a beam is possible, therefore, because each component is reflected in a direction different from any of the others. By rotation of a crystal to vary the angle

of incidence it is then possible to spread out a beam of x rays into first, second, third order spectra, just as in the case of the diffraction grating. Frequently we are concerned only with the first order and in this book we shall confine our attention to that order.

101 X Ray Spectrometer — A common arrangement for applying the above principle to the analysis of a beam of x rays is shown in Fig. 111. A narrow beam of rays, after passing through the slits S_1 and S_2 cut in thick blocks of lead, is incident on the face of a crystal C set on the table of the spectrometer. By means of a scale rotations of the crystal through small angles may be measured accurately. A third slit S_3 is so placed that any reflected beam which exists may enter an ionization chamber I placed immediately behind it. This slit must of course be placed so that the line OS_3 makes the same angle with the face of the crystal as the incident beam. Since for each position of the crystal there is only a single correct position of the

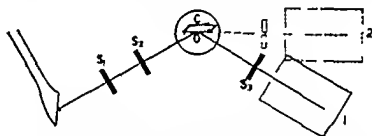


FIG. 111 Diagram showing the essential of an x-ray spectrometer with ionization chamber

slit S and the ionization chamber these are mounted on an arm by means of which they may be rotated about the central axis through O .

In actual use, the incident beam of rays to be analyzed is allowed to strike the face of the crystal at a number of different angles. For each angle slit S_3 and the ionization chamber are set in the correct position and the ionization current, if any measured. A graph is then made showing the way in which the ionization current varies with the angle of incidence. Alongside the axis on which angles of incidence are plotted a wave length scale may be marked by using the fundamental relation $\lambda = 2d \sin \theta$ provided that a crystal with known d is used. Examples of such graphs are given in Fig. 113 and Fig. 114. These will be discussed presently.

102 X Ray Spectrograph. — The ionization chamber may be replaced by a photographic plate and a permanent record obtained of the x ray spectrum. By way of illustration reference is made to the *Seaman Spectrograph* an instrument, especially designed for radiologists, which is small and compact and does

a cleavage plane of a crystal with its very regular arrangement of atoms, acts as a mirror for x rays, nature providing the smooth surface necessary to reflect regularly waves as short as those of x rays. The reflection of x rays from a crystal, however, differs in one important respect from optical reflection at a mirror. Since x rays penetrate matter, there is a series of reflections from successive parallel planes of atoms. The beam CD , therefore, in reality consists of a number of superimposed beams, each reflected from a different plane of the crystal.

Now let us enlarge the scale of our diagram sufficiently to show successive layers, as we have done in Fig 110, for four layers. Then, remembering that

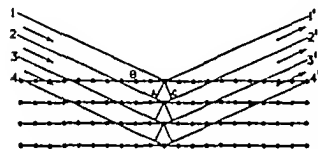


FIG. 110. Reflection of x-rays from successive parallel planes of atoms in a crystal.

the planes are separated distances not much greater than 10^{-8} cm, we see that even a narrow beam like AC when enlarged on the same scale, will, in Fig 110, be represented by several lines such as 1, 2, 3, 4 with corresponding reflected rays $1'$ 2, $3'$ 4. Moreover, it is not difficult to see that the path of the disturbance along

11 is shorter than that along $22'$ $22'$ shorter than $33'$ and so on. For disturbances 11 and $22'$ this path difference is equal to $AB + BC$ as shown in Fig 110. With a little simple trigonometry, this can readily be shown to be equal to $2d \sin \theta$ where d is the distance between successive layers, and θ is the angle which the beam of rays makes with the face of the crystal. For any successive pairs of disturbances, the path difference will be the same.

We see then that the beam CD of Fig 109, really consists of a superposition of a number of beams, with a path difference between every successive pair equal to $2d \sin \theta$. Just as with a diffraction grating and ordinary light (see section 89) it follows that all the component beams will unite to form a resultant intense beam only if this path difference is equal to one, or two, or three or more wave lengths. This means that when a beam of homogeneous x rays is incident on the face of a crystal, there is a reflected beam of marked intensity only for very special angles of incidence. If the incident beam contains a number of different wave lengths then, for any given angle of incidence there is an intense reflected beam only if there is a component whose wave length λ is such that $\lambda = 2d \sin \theta$ or $2\lambda = 2d \sin \theta$ etc. Analysis of a beam is possible, therefore, because each component is reflected in a direction different from any of the others. By rotation of a crystal to vary the angle

two quantities are connected by the following simple relation

$$\text{shortest wave length (in angstroms)} = \frac{12345^*}{\text{maximum voltage}}$$

For example, with 80 000 volts as peak value, the shortest wave length is about 0.15 angstrom. With 250 000 volts, the shortest is 0.049 angstrom. Although the shortest wave length is not the most intense (note again the graphs of Fig. 113) a knowledge of its value gives some indication of the quality of the beam.

If the shortest wave length can be read off a scale provided with such an instrument as the Seeman Spectrograph the above relation provides us with an accurate method of measuring tube voltage. (See again section 28.)

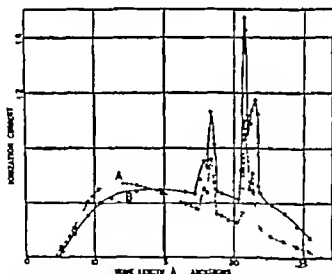


FIG. 114. Graphs showing the presence of characteristic x-rays, *A* with filter 1 mm. of copper; *B* with filter 12 mm. of aluminum.

104 General and Characteristic Radiations. — An examination of Fig. 113 and Fig. 114 will show that the graphs differ in one important respect. In each of those in Fig. 113 the radiation covers a continuous range, beginning at the critical minimum wave length then rapidly increasing to a region of maximum intensity beyond which the intensity gradually decreases until the radiation ceases. In each of the graphs of Fig. 114 there is an additional feature, because isolated peaks of marked intensity occur at certain critical wave lengths.

12354 is more accurate but an accuracy of less than one per cent is quite sufficient in radiology work and the easily remembered 12345 may be used.

not require as much experimental skill as the above spectrometer. The beam to be analyzed enters the instrument through a narrow slit S_1 . Fig. 112, is incident on the face of a crystal immediately behind which a second narrow slit S_2 allows any reflected beam which may be present to emerge and strike a

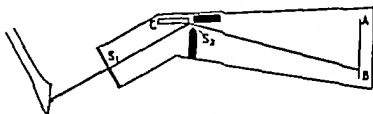


FIG. 112. The Seeman x-ray spectroph.

photographic plate in position AB . By means of a clock work mechanism the portion of the instrument holding the crystal and the plate is kept in a regular oscillatory motion about the second slit as axis. In this way the original beam

strikes the crystal behind S_2 at a series of different angles and regular reflection of each component takes place in the way we have already described. Wave lengths may be calculated by the use of $2d \sin \theta$ but actually the manufacturer of this instrument provides a scale by means of which wave lengths may be read off directly from the photographic plate.

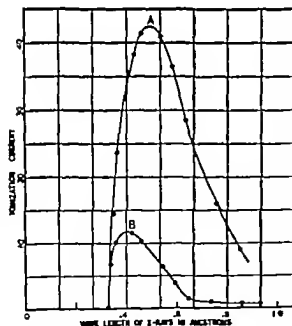


FIG. 113. Graphs showing the analysis of a general beam of x-rays by a spectrometer: A without filter B with filter

103 Shortest Wave Length.—The graph of Figs. 113 and 114 made from observations by the late Dr. Duane, a prominent x-ray worker at Harvard University, are typical of results obtained with the ionization chamber. The graphs show clearly two things: (1) there is always a range of wave lengths in the beam

leaving the target of a tube; and (2) there is a very critical minimum wave length at which radiation begins. Experiment shows that this shortest wave length depends solely on the *maximum* voltage across the tube, and that these

two quantities are connected by the following simple relation

$$\text{shortest wave length (in angstroms)} = \frac{12345^*}{\text{maximum voltage}}$$

For example, with 80 000 volts as peak value the shortest wave length is about 0.15 angstrom. With 250 000 volts, the shortest is 0.049 angstrom. Although the shortest wave length is not the most intense (note again the graphs of Fig. 113) a knowledge of its value gives some indication of the quality of the beam.

If the shortest wave length can be read off a scale provided with such an instrument as the Seeman Spectrograph the above relation provides us with an accurate method of measuring tube voltage. (See again section 28.)

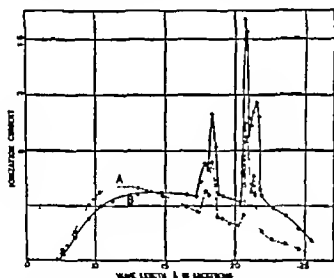


FIG. 114. Graphs showing the presence of characteristic x-rays; *A* with filter 1 mm. of copper; *B* with filter 12 mm. of aluminum.

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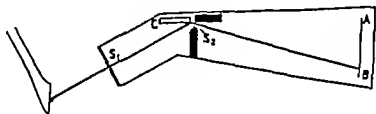


FIG. 112. The Seeman x-ray spectrograph.

photographic plate in position AB . By means of a clock work mechanism the portion of the instrument holding the crystal and the plate is kept in a regular oscillatory motion about the second slit as axis. In this way the original beam

strikes the crystal behind S_2 at a series of different angles and regular reflection of each component takes place in the way we have already described. Wave lengths may be calculated by the use of $2d \sin \theta$ but actually the manufacturer of this instrument provides a scale by means of which wave lengths may be read off directly from the photographic plate.

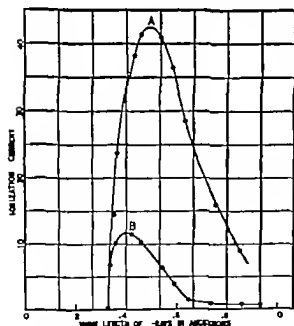


FIG. 113. Graphs showing the analysis of a general beam of x-rays by a spectrometer A without filter B with filter

103 Shortest Wave Length.—The graph of Figs. 113 and 114 made from observations by the late Dr. Duane, a prominent x-ray worker at Harvard University are typical of results obtained with the ionization chamber. The graphs show clearly two things (1) there is always a range of wave lengths in the beam

leaving the target of a tube; and (2) there is a very critical minimum wave length at which radiation begins. Experiment shows that this shortest wave length depends solely on the *maximum* voltage across the tube, and that these

(2) *The Tube Voltage* — Double the voltage and the intensity is increased approximately four times or the intensity varies approximately as the square of the voltage

(3) *The Atomic Number of the Metal Used as a Target* — The higher the atomic number, the more intense is the beam

106. *Characteristic Rays*. — Characteristic rays do not appear at all unless the tube voltage is sufficiently high. That is the reason none appear in the graphs of Fig 113 nor in spectrum 10 of Fig 115. With tungsten as target, potentials in the range 80 000 to 100 000 are necessary and with uranium characteristic rays are not emitted until nearly 115 000 volts are applied to the tube. The necessary voltage is proportional to the square of the atomic number. Thus, platinum of atomic number 78 requires a voltage which is higher than that for tungsten atomic number 74 by the factor

$$\frac{78 \times 78}{74 \times 74}$$

It is well to note that, the higher the atomic number the shorter the wave length of corresponding* rays. This point is illustrated by the numbers given in Table XIX

TABLE XIX — CORRESPONDING WAVE LENGTHS OF FOUR ELEMENTS

	Copper	Silver	Tungsten	Uranium
Wave Length	1.54	.56	.21	.15
Atomic Number	29	47	74	92

107 *Wave Length and Penetration*. — Wave length measurements show that in radiology the range extends from about 1.0 to possibly 0.05 angstrom. By means of the spectrometer a beam may be separated into its constituent wave lengths and the absorption of each examined separately. The results of such investigations show that in general† the shorter the wave length, the more penetrating the beam. For example using the numbers given in first and fourth columns of Table XX we note that for $\lambda = 0.064$ the H.V.L. in aluminum is 19.7 mm; for $\lambda = 0.13$ 13.7 mm; and for $\lambda = 0.26$ 6.35 mm. For the same three wave lengths, the H.V.L. in copper are 3.9 mm., 1.36 mm. and 0.24 mm.

In section 110 the meaning of corresponding wave lengths is explained.

† See, below section 120

The same two types of x ray radiation are shown photographically in Fig 115, in which each spectrogram corresponds to a different tube voltage. These photographs show clearly (a) the continuous radiation, beginning at a critical wave length, whose magnitude varies with the applied voltage; and

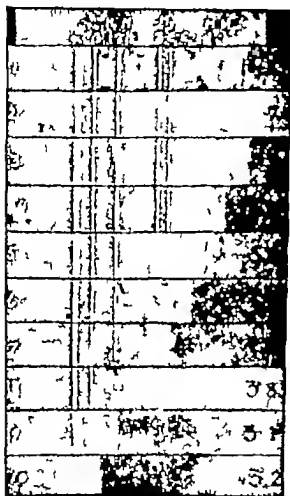


FIG. 115. Spectrograms showing short wave-length limits at different voltages, as well as characteristic rays. (Rosa)

ent, depend on the nature of the target. The continuous range is called the *general* or *white* or *independent* radiation; the isolated wave lengths, the *characteristic* radiation.

105 White Radiation. — The total intensity of the beam of continuous rays depends on the following factors

(1) *The Current through the Tube* — Double the current, and the intensity is doubled; or more generally the intensity is directly proportional to the current.

(b) the superposition, in all but number 10, of isolated wave lengths.

The difference between the two kinds of x ray spectra has an exact optical analogy. If the light from a white hot carbon of an arc lamp is examined with a spectroscope, one observes a continuous spectrum with all colors ranging from red to violet. If the carbon arc is fed with a small quantity of a salt, barium, for example, one sees superimposed on the continuous spectrum isolated narrow spectral lines. Any white hot object will give a continuous spectrum, but the number and the position of the isolated spectrum lines depends on the material put into the arc.

In the same way an x ray tube with any metal as target, and operated on any voltage emits a continuous range of wave lengths, whereas the values of the isolated wave lengths, which are sometimes although not always present,

(2) *The Tube Voltage* — Double the voltage, and the intensity is increased approximately four times or the intensity varies approximately as the square of the voltage.

(3) *The Atomic Number of the Metal Used as a Target* — The higher the atomic number the more intense is the beam

106. *Characteristic Rays.* — Characteristic rays do not appear at all unless the tube voltage is sufficiently high. That is the reason none appear in the graphs of Fig 113 nor in spectrum 10 of Fig 115. With tungsten as target, potentials in the range 80 000 to 100 000 are necessary and with uranium characteristic rays are not emitted until nearly 115 000 volts are applied to the tube. The necessary voltage is proportional to the square of the atomic number. Thus, platinum of atomic number 78 requires a voltage which is higher than that for tungsten atomic number 74 by the factor

$$\frac{78 \times 78}{74 \times 74}$$

It is well to note that, the higher the atomic number the shorter the wave length of corresponding* rays. This point is illustrated by the numbers given in Table XIX.

TABLE XIX — CORRESPONDING WAVE LENGTHS OF FOUR ELEMENTS

	Copper	Silver	Tungsten	Uranium
Wave Length	1.54	56	21	15
Atomic Number	29	47	74	92

107 *Wave Length and Penetration.* — Wave length measurements show that in radiology the range extends from about 10 to possibly 0.05 angstrom. By means of the spectrometer a beam may be separated into its constituent wave lengths and the absorption of each examined separately. The results of such investigations show that in general† the shorter the wave length, the more penetrating the beam. For example using the numbers given in first and fourth columns of Table XX we note that for $\lambda = 0.064$ the H.V.L. in aluminum is 19.7 mm. for $\lambda = 0.13$ 13.7 mm. and for $\lambda = 0.26$ 6.35 mm. For the same three wave lengths, the H.V.L. in copper are 3.9 mm., 1.36 mm., and 0.24 mm.

In section 110 the meaning of corresponding wave lengths is explained.

† See, however section 120

TABLE XX—HALF VALUE LAYERS FOR A FEW WAVE LENGTHS
Aluminum

λ	μ/ρ^*	μ	H.V.L.
0.064	130	351	19.7 mm.
0.098	156	421	16.4
13	186	502	13.7
175	228	616	11.2
2	270	729	9.5
26	402	1 685	6.35

Copper

λ	μ/ρ^*	μ	H.V.L.
0.064	198	1 76	3.9 mm.
0.098	325	2 89	2.38
13	57	5 07	1.36
175	1 12	9 97	.69
2	1 59	14 15	.49
26	3 25	28 9	.24

The meaning of these symbols is explained in sections 122 and 123.

108. K, L, and M Rays. — An analysis of all the characteristic wave lengths emitted by a single element shows that they may be divided into groups. Table XXI for example gives the wave lengths in angstroms of three groups emitted by the element tungsten

TABLE XXI—CHARACTERISTIC RAYS OF TUNGSTEN*

K	L	M
213	1 43	5 16
208	1 47	5 34
185	1 23	5 62
184	1 24	6 07
179	1 09	6 12
		6 74
		6 79
		6 93
		6 95
		6 97
		7 34
		8 56
		8 94
		8 98

* Values taken from *X-Rays in Theory and Experiment* by Compton and Allison, D. Van Nostrand Company

In accordance with certain theoretical ideas to be explained presently, the three groups are designated K, L and M. A glance at the table will show that none of the wave lengths in the L and M groups are of any use in radiology. They are so soft that the walls of an ordinary tube would absorb them.

109 Interpretation of K, L and M Wave Lengths. — In order to give an explanation of the origin of characteristic wave lengths and their arrangement in groups, it is necessary to amplify somewhat the picture of an atom given in section 36. It was there pointed out that an atom of atomic number Z consists of a nucleus with a positive charge of Z electronic units surrounded by Z electrons. The student's work in chemistry will have made him familiar with outer valency electrons, one or more of which may be detached from the parent atom leaving a positive ion. In the sodium family, for example, a single valency electron is the distinguishing mark which accounts for the similarity in the chemical properties of the members of this family. Normally, a sodium atom is a stable system with the valency electron in equilibrium because it is revolving about the remainder of the atom in what we shall now call its innermost orbit.

Suppose, however that we have a sodium salt in a flame which is emitting the yellow light characteristic of sodium. What now is the state of the atom and what is happening to cause the emission of characteristic sodium light? The main features of the answers to these questions were given in 1913 by the Danish physicist Bohr who at that time, was trying to interpret the characteristic spectrum of luminous hydrogen. According to Bohr's ideas an atom cannot emit radiation which represents energy unless previously it has had energy communicated to it. This, of course is what is to be expected from the law of conservation of energy. If by any means, such as the impact of a moving electron, the outer valency electron is moved farther away from the nucleus than its normal position work must be done against the force of attraction on the valency electron and in consequence there is an increase in the energy of the atomic system. If now the electron subsequently returns to its normal position or part way to it, radiant energy is emitted in an amount equal to the loss arising from the return of the electron.

To explain the limited number of isolated characteristic wave lengths in the spectrum Bohr assumed (1) that the valency electron could occupy only certain definite orbits; and (2) that for each transition from an outer to an inner orbit, a corresponding wave length is emitted. In Fig 116, for example, if the inner circle represents the normal stable orbit of the electron in the hydrogen atom and the dotted circles the possible outer or virtual

TABLE XX—HALF VALUE LAYERS FOR A FEW WAVE LENGTHS
Aluminum

λ	μ/ρ	μ^*	H.V.L.
0.064	130	351	19.7 mm.
0.098	156	421	16.4
13	186	502	13.7
175	228	616	11.2
2	270	729	9.5
26	402	1.685	6.35

Copper

λ	μ/ρ^*	μ^*	H.V.L.
0.064	198	1.76	3.9 mm.
0.098	325	2.89	2.38
13	57	5.07	1.36
175	1.12	9.97	.69
2	1.59	14.15	.49
26	3.25	28.9	.24

The meaning of these symbols is explained in sections 122 and 123.

108. K, L and M Rays. — An analysis of all the characteristic wave lengths emitted by a single element shows that they may be divided into groups. Table XXI for example gives the wave lengths in angstroms of three groups emitted by the element tungsten.

TABLE XXI—CHARACTERISTIC RAYS OF TUNGSTEN*

K	L	M
213	1.48	5.16
208	1.47	5.34
185	1.28	5.62
184	1.24	6.07
179	1.09	6.12
		6.74
		6.79
		6.93
		6.95
		6.97
		7.34
		8.56
		8.94
		8.98

Values taken from *X-Rays in Theory and Experiment* by Compton and Allison, D. Van Nostrand Company

have led physicists to the view that the electrons are arranged around the nucleus at increasing distances, in groups or shells, as they are sometimes called, designated by the letters K, L, M N O, or by the numbers 1 2, 3 4 5. Moreover there is much evidence that the inner or K shell has 2 electrons; the L 8 (subdivided into subshells) the M 18 (subdivided into subshells) the N 32 and so on. If now an atom is ionized by the removal of an electron from the innermost or K shell much more work is necessary than that required to remove an electron from the L ring. This should be clear if it is realized that the electron in the K ring being nearest the nucleus, is much more strongly attracted than when farther away as in an L or M or N ring. Moreover the repulsive forces arising from the surrounding electrons also make it more difficult to remove an electron from the K than from any of the outer shells.

In order to put an atom in the state where the emission of all of its characteristic x rays is possible, first of all the atom must be ionized by the removal of an electron from the K shell. This may be done by electronic bombardment of a target, or as we shall see in the next chapter by absorption of a beam of x rays of suitable wave length. When an electron has been so removed, its place subsequently is filled by another electron coming in or "dropping" in from one of the surrounding shells. If the drop is from the L shell there is a certain energy gain and a characteristic ray of a definite wave length is emitted. If the drop is from the M shell to the K shell, the energy gain is greater and a shorter wave length is emitted. For a drop from the N shell to the K shell, the emitted wave length is still shorter.

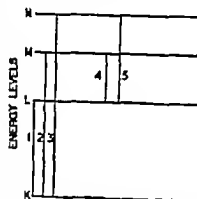


FIG. 117 Schematic diagram to depict the emission of K x-ray wave lengths by electron transitions to the K shell; and of L wave lengths by transitions to the L shell.

The K group of wave lengths, then corresponds to electron drops or transitions from various outer shells or energy levels into the K level. In Fig 117, 1 2 and 3 represent three wave lengths in this group.

If an electron has dropped from the L to the K level, the vacancy thus created in the L shell must be filled, and hence we have an L group of wave lengths corresponding to transitions from outer levels to the L level. In Fig 117 4 and 5 represent two such wave lengths. Because of the smaller change in energy involved in transitions which end on the L level instead of the K, the corresponding wave lengths are longer. (See again Table XXI.)

In the same manner we may have an N group of still longer wave lengths

orbits, the lines with the arrow heads represent some of the possible transitions which give rise to corresponding emitted wave lengths. All this can be put in mathematical language and the results tested numerically, but in this book we shall consider only the quantitative aspect which connects wave length with the energy change

For each electron transition or jump, a *quantum* or packet of radiant energy is emitted. The magnitude of a quantum is $h\nu$, where h is a definite quantity called Planck's constant in honor of the physicist who first introduced the conception of quanta, and ν is the frequency of the emitted radiation. Since $\text{frequency} = \frac{\text{velocity}}{\text{wave length}}$ or $\nu = \frac{c}{\lambda}$, where c is the velocity of all electromagnetic waves, we may write

$$h\nu = \frac{hc}{\lambda} = \text{energy change resulting from the electron jump, or}$$

$$\frac{1}{\lambda} = \frac{\text{energy change}}{hc}$$

It follows that *the greater the energy change, the shorter the wave length emitted.* Referring again to Fig 116 we see

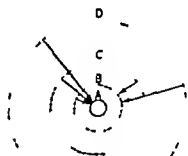


FIG. 116. When an electron falls from an outer to an inner orbit, energy is radiated.

that when an electron falls from orbit D to A the wave length emitted is shorter than for the fall C to A ; a fall from D to B gives rise to a shorter wave length than from C to B ; and so on.

In examining optical spectra, it is found that members of the same chemical family have features in common, and that an abrupt change takes place when we pass from one family in the periodic table to the next. In x ray spectra, however there is no such periodic change. We have already made reference to one example of this, when in section 106 it was pointed out that, as the atomic number of an element gets larger

and larger the wave lengths of corresponding x rays steadily become shorter and shorter. This fact, combined with many others, suggests that the emission of characteristic x rays is related, not to outer valency electrons, but to electrons which in heavy elements are very much nearer the nucleus.

To form some sort of picture of the origin of characteristic x rays, we must examine a little more carefully the structure of atoms, particularly those of elements containing many electrons. A large number of experimental facts

have led physicists to the view that the electrons are arranged around the nucleus at increasing distances, in groups or shells, as they are sometimes called, designated by the letters K, L, M, N, O or by the numbers 1, 2, 3, 4, 5. Moreover there is much evidence that the inner or K shell has 2 electrons, the L, 8 (subdivided into subshells), the M, 18 (subdivided into subshells); the N, 32; and so on. If, now, an atom is ionized by the removal of an electron from the innermost or K shell, much more work is necessary than that required to remove an electron from the L ring. This should be clear if it is realized that the electron in the K ring being nearest the nucleus, is much more strongly attracted than when farther away as in an L or M or N ring. Moreover the repulsive forces arising from the surrounding electrons also make it more difficult to remove an electron from the K than from any of the outer shells.

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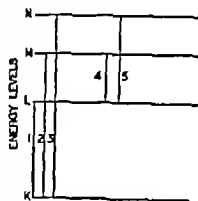


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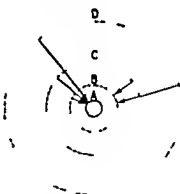


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and larger the wave lengths of corresponding x rays steadily become shorter and shorter. This fact, combined with many others, suggests that the emission of characteristic x rays is related, not to outer valency electrons, but to electrons which in heavy elements are very much nearer the nucleus.

To form some sort of picture of the origin of characteristic x rays, we must examine a little more carefully the structure of atoms, particularly those of elements containing many electrons. A large number of experimental facts

have led physicists to the view that the electrons are arranged around the nucleus at increasing distances, in groups or shells, as they are sometimes called designated by the letters K, L, M, N, O, ; or by the numbers 1 2 3 4 5. Moreover there is much evidence that the inner or K shell has 2 electrons the L, 8 (subdivided into subshells) the M 18 (subdivided into subshells); the N 32; and so on. If now an atom is ionized by the removal of an electron from the innermost or K shell much more work is necessary than that required to remove an electron from the L ring. This should be clear if it is realized that the electron in the K ring, being nearest the nucleus, is much more strongly attracted than when farther away as in an L or M or N ring. Moreover the repulsive forces arising from the surrounding electrons also make it more difficult to remove an electron from the K than from any of the outer shells.

In order to put an atom in the state where the emission of all of its characteristic x rays is possible, first of all the atom must be ionized by the removal of an electron from the K shell. This may be done by electronic bombardment of a target, or as we shall see in the next chapter by absorption of a beam of x rays of suitable wave length. When an electron has been so removed, its place subsequently is filled by another electron coming in or "dropping in from one of the surrounding shells. If the drop is from the L shell there is a certain energy gain and a characteristic ray of a definite wave length is emitted. If the drop is from the M shell to the K shell, the energy gain is greater and a shorter wave length is emitted. For a drop from the N shell to the K shell, the emitted wave length is still shorter. The K group of wave lengths, then, corresponds to electron drops or transitions from various outer shells or energy levels into the K level. In Fig 117, 1 2 and 3 represent three wave lengths in this group.

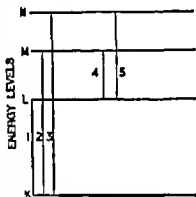


FIG. 117 Schematic diagram to depict the emission of K x-ray wave lengths by electron transitions to the K shell and of L wave lengths by transitions to the L shell.

If an electron has dropped from the L to the K level, the vacancy thus created in the L shell must be filled, and hence we have an L group of wave lengths corresponding to transitions from outer levels to the L level. In Fig 117 4 and 5 represent two such wave lengths. Because of the smaller change in energy involved in transitions which end on the L level instead of the K, the corresponding wave lengths are longer. (See again Table XXI.)

In the same manner we may have an N group of still longer wave lengths

corresponding to transitions of an electron from outer shells or levels to the N level.

In Table XXI, it will be noted, especially for the M group, that more wave lengths are listed than might be expected from the above explanation. This is due to the fact that the electrons in any one shell or level such as the M, are arranged in subshells, and that, in consequence, the energy change when an electron goes from one subshell of the M level to the K level, is slightly different from the change corresponding to a transition from another subshell of the M level to the K level.

110 Meaning of Corresponding Wave Lengths. — In section 106 reference was made to the fact that the greater the atomic number of an element, the shorter the wave length of a corresponding ray (See again Table XIX). By corresponding rays we mean those which arise from the same transition in energy levels. Thus, for all elements, the wave lengths emitted when an electron drops from the L level to the K, or more exactly from the same sublevel of the L shell to the K, are corresponding. The reason why the wave lengths of such rays get shorter as the atomic number Z gets larger, should now be evident. The greater Z , the greater the positive charge on the nucleus, hence the greater the attraction of the nucleus for a K electron, hence the greater the work which must be done to remove a K electron out of its shell. When an electron returns to the K shell, there is, therefore, a greater loss in energy and a shorter wave length is emitted.

111 Effective Wave Length. — In the above sections we have explained how a beam of x rays may be analyzed into its constituent wave lengths. Although such an analysis is the ideal way of describing the quality of a beam, the practical radiologist can scarcely be expected to examine quality in this way. He can, however, make use of wave length measurements obtained by other workers under laboratory conditions and by means of them record what is called the *effective wave length* of the beam he is utilizing. The meaning of effective wave length may be defined in several ways.

(1) In terms of H.V.L.

Suppose an operator is provided with a table giving the H.V.L. in copper for a series of monochromatic wave lengths, such as we have given in Table XX. If, then, without any analysis into constituent wave lengths, he determines the H.V.L. for the beam he is using, he can read off from his table the wave length of the monochromatic beam which has this same H.V.L. That wave length would then be taken as the effective wave length of his beam.

(2) Through the absorption of a particular thickness of a standard substance

It is a simple matter to determine the percentage reduction in intensity of an unanalyzed beam brought about by say $\frac{1}{2}$ mm of copper. This requires only two readings with an instrument like an electroscope, one of the rate of fall before the introduction of the layer of copper the other after the copper is in place. (See Chapter XII) If now the operator is provided with a graph or a table giving the percentage absorption of $\frac{1}{2}$ mm of copper for a whole range of monochromatic wave lengths, he again can read off the value of that particular wave length which has the same percentage absorption as that of the beam he is using. This gives him his effective wave length.

Alternately from the percentage absorption by the copper of the beam under examination it is not difficult to calculate the absorption coefficient. (See section 122) Then from a formula connecting the coefficient with the wave length the value of the monochromatic wave length which has this same coefficient can be calculated. This gives the effective wave length.

When this method is used, care must be exercised to specify the particular thickness of standard absorbing material used, because somewhat different values of λ are obtained for each thickness. For example, in one investigation Dr Edith Quimby, of the Memorial Hospital, New York, showed that with a $1/10$ mm of copper 59% of a beam was transmitted, and λ was found to be 0.235 angstrom with 0.47 mm of copper 50% was transmitted, and λ was 0.208 angstrom; and with a layer of copper 1 mm. thick, the transmission was 35% and λ 0.182 angstrom

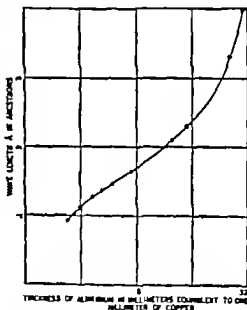


FIG 118. Standard graph (after Duane) for determining effective wave length.

(3) Through the ratio of equivalent thicknesses of two standard substances.

The graphs of Fig 114 illustrate the important fact that the *relative* absorbing powers of two different substances vary with the wave length. From these graphs, for example we note that 1 mm. of copper is a more effective absorber than 12 mm. of aluminum for wave lengths longer than 0.141 angstrom but less effective for shorter wave lengths. Expressing this fact in another way we say that the particular thickness of aluminum which absorbs a beam of x rays to the same extent as 1 mm of copper varies with

corresponding to transitions of an electron from outer shells or levels to the N level

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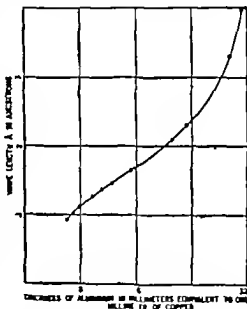


FIG. 118 Standard graph (after Duane) for determining effective wave length.

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CHAPTER XI

SECONDARY X RAYS AND ABSORPTION

113 Secondary X Rays. — In this chapter we discuss in detail what happens when a beam of x rays is reduced in intensity by passage through an absorbing layer. Suppose we arrange an x ray tube and an electroscope as in Fig 119 so that no part of the *primary* beam leaving the target can enter the window of the electroscope. On operating the tube we find that the leaf falls very slowly. If, however a block of wood *R* is placed in the path of the primary beam, the electroscope is discharged more quickly. This increased ionization is due to the emission by the wood of what are called *secondary* x rays. The experiment illustrates the important principle that, whenever x rays fall on matter there is a re-emission in all directions, of secondary x rays. This fact must never be forgotten. To stand out of the direct path of a beam of x rays by no means insures protection from them for we may be bathed in rays from objects against which the primary beam strikes.

Investigations regarding the nature of secondary x rays show that there are in general two kinds (1) *scattered rays*, which to a first approximation are of the same wave length as the original primary beam and (2) *characteristic fluorescent rays* which are characteristic of the material of the radiator being in fact identical with the characteristic x rays emitted by the same material when used as the target of an x ray tube.

An optical analogy will perhaps help to make the difference between the two kinds clear. If there is much dust in a darkened room it is an easy matter to see a beam of light from an arc lantern. If a red glass is placed in front of the arc the beam appears red because red light is reflected by the dust particles in all directions. Now the phenomenon of scattering of x rays, while not exactly the same is not unlike this scattering of light in all

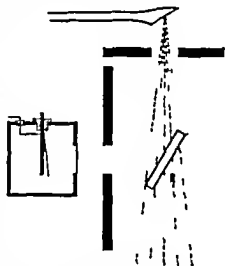


FIG. 119 Experimental arrangement to show existence of secondary x-rays.

the wave length. Such equivalent thicknesses of aluminum, as determined by Duane, are plotted in Fig. 118. By means of such a graph an operator can determine the effective wave length of a beam in still another way. All that is necessary is to determine by actual experiment (1) how much the beam is reduced in intensity by 1 mm. of copper; and (2) by using increasing thicknesses of absorbing layers of aluminum, the particular thickness which reduces the intensity of the beam by the same amount as the millimeter of copper. Suppose the equivalent thickness of aluminum was 16 mm. Then from this graph, we read off that, for a monochromatic wave length equal to 0.17 angstrom, 16 mm. of aluminum absorbs to the same extent as 1 mm. of copper. By this method then 0.17 angstrom is the effective wave length of the mixed beam.

112. Relation of Focal Spot to Wave Length. — In earlier pages reference has been made to differences in the size of the focal spots on the targets of tubes. Before concluding this chapter, it is desirable to look at this question in the light of our knowledge that x rays are short ether waves. Since this is the case, in radiography and fluoroscopy the radiologist is dealing with shadow pictures, the details of which should be as clearly defined as possible. To obtain good detail sharp shadows are necessary and these can only be obtained by having a small source of rays, that is, a fairly fine focal spot. The case is exactly analogous to the shadow patterns of obstacles placed in the path of light rays. A small source of light such as *P* Fig. 60*a* (an uncovered arc lamp for example), casts a sharp shadow of an object *O* on a screen. If, however, the source of light is comparable in size with the object, as shown in Fig. 60*b* the portion of the shadow *AB* will be completely dark, whereas around it will be a region which receives light from some parts of the source, but which is cut off from other parts. The shadow is not sharp. In radiography it is exactly the same, and for good pictures it is necessary to have as fine a focus as the energy conditions will allow. However care should be exercised that rays generated from parts of the tube other than the focal spot (as sometimes happens, since wherever electrons hit, x rays originate) are not allowed to fall on the body to be examined.

On the other hand, in treatment, it is a question solely of the absorption of radiation and there is no need whatever to have a fine focus. Indeed, as in treatment a tube is generally operated continuously for some time, it is highly desirable that too fine a focal spot be not used.

change is 0.0486 angstrom. Hence, for a primary beam of wave length 0.2 angstrom, the scattered beam observed in a direction at right angles to the primary, has a wave length 0.2243 angstrom. If the primary beam is of very short wave length, 0.05 for example, the percentage change in the wave length of the scattered rays is considerable, this wave length being changed to 0.0743 at 90° and 0.0986 at 180° .

The reason for this change in wave length is given in section 118

115 Characteristic Radiation. — (1) As already noted, fluorescent characteristic rays are identical with the characteristic rays previously discussed (section 106) the difference between the two being solely in their mode of generation. Fluorescent rays result from the stimulus of an existing primary beam of x rays, not from the impact of electrons against a target.

(2) To excite fluorescent rays of the K group the wave length of the primary beam must be shorter than that of any of the characteristic rays in this group. Since the shortest wave length emitted by any of the first 35 elements in the periodic table is longer than 1 angstrom and for elements with atomic numbers between 35 and 63 exceeds 0.3 angstrom this condition is generally fulfilled for beams utilized in radiology at any rate for all elements except those of high atomic weight. To excite the K characteristic rays of an element like tungsten however a primary wave length shorter than 0.18 is necessary for platinum shorter than 0.16 and for lead, shorter than 0.14 angstrom.

In this connection an important point relating to filtration arises. Suppose a primary beam contains a mixture of hard and of soft rays and that a filter of copper is used to remove the soft components. In traversing the copper the hard primary rays will excite the characteristic rays of copper and hence these will emerge from the filter as well as a portion of the original hard beam. Now characteristic rays of copper are soft and may give rise to the injurious effect which the filter is put in to prevent. A second substance, aluminum for example whose characteristic rays are still softer than copper should then be used on the side of the copper remote from the tube. This substance will then absorb the soft secondary rays of copper but its own characteristic rays will do no harm because they are so much longer than those of copper that even a short thickness of air absorbs them.

(3) *Relative to scattered radiation*, characteristic becomes more important for longer wave lengths. In tissue for example to quote from Mayneord* for $\lambda = 0.2$ angstrom the absorption is 90 per cent. scatter and 10 per cent. fluorescent absorption while at 1 angstrom some 18 per cent. only is due to scatter. Since the wave lengths utilized in deep therapy are often even

* Mayneord, *The Physics of X Ray Therapy* p. 41 (Churchill, London.)

directions by dust particles. It consists in a re-emission in all directions of rays of approximately the same kind as the primary beam.

Again if certain substances are placed in the path of the beam from an arc light, or in direct sunlight, they are seen to fluoresce with a brilliant and characteristic color. Uranium glass, for example, emits a brilliant greenish light in this way; a solution of sulphate of quinine in sulphuric acid shows a characteristic and beautiful blue, and so on for many other substances. This fluorescent light is characteristic of the substance and is caused by the excitation of the primary beam of light falling on it. Characteristic fluorescent x rays are closely analogous. They are characteristic of the substance and result from its stimulation by a primary beam.

114 Scattered Radiation. — We note certain details of importance in radiology

(1) Scattered rays are emitted in all directions (even backwards) by the radiator but with a maximum intensity in the forward direction, that is, in the same direction as the primary beam. The shorter the wave length the greater the intensity scattered in the forward direction.

(2) For elements of low atomic weight and a primary beam of short wave length, say not exceeding 0.25 angstrom, scattered radiation is of greater importance than characteristic. Since tissue is made up almost entirely of the light elements hydrogen, carbon, oxygen and nitrogen this means that when a beam of short wave length traverses tissue, scattered rays are of very great importance. Further reference will be made to this question.

(3) When scattered rays were first studied, it was considered that their wave length was exactly the same as that of the primary beam. Further experiments, however, particularly those of J. A. Gray and A. H. Compton, showed that the scattered beam consists of a mixture of *unmodified* rays, that is, those whose wave length is the same as that of the primary beam, and *modified* rays, those whose wave length is different. For light elements and a primary beam of short wave length the intensity of the modified beam is relatively much greater than that of the unmodified, a fact which means that there is a progressive softening of a beam or lengthening of wave length, when it traverses tissue.

The magnitude of this change in wave length depends on the direction in which the scattered rays are being observed. If ϕ is the angle the scattered beam under observation makes with the primary beam Compton showed that $\Delta\lambda$, the change in wave length is given by the relation

$$\Delta\lambda = 0.0243 (1 - \cos \phi) \text{ angstrom.}$$

Thus, for $\phi = 90^\circ$, the change is 0.0243 angstrom; for $\phi = 180^\circ$ the

The idea on which the experiment is based is really a very simple one. When air is laden with moisture a fog will form much more readily if dust is present than if the air is dust free. It has been said that if all the sooty smoke which pollutes the air over the city of London could be consumed or in some way prevented from leaving chimneys, fogs would be neither thicker nor more prevalent over that city than elsewhere in England. The suggestion is based on sound physics, because water condenses readily when little particles of dust or dirt are present to act as nuclei around which drops can form. Now Wilson showed that *ions also act as nuclei for the formation of water drops*. In the actual experimental arrangement ions are formed by an ionizing agent in moisture laden but dust free air. The air is allowed to expand suddenly and thereby be cooled, water condenses on the ions, and a flash of light enables a photograph to be taken. *For each unstable ion a visible drop appears.*

In Fig 120 then each little white dot represents a droplet of water and hence an ion. The student should have no difficulty in tracing the irregular paths of some of the photoelectrons since they mark their trails by the ions they have formed.

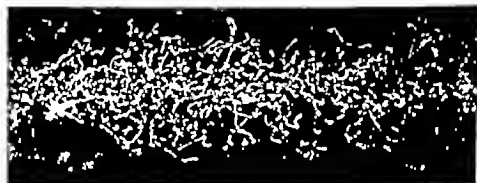
118. Recoil Electrons and Scattering — To obtain characteristic rays a photoelectron must be ejected from the atom. Scattered rays, on the other hand, arise from the impact of the primary beam against an electron which is comparatively free, that is, an electron not strongly held by the attraction of the nucleus of an atom. To explain the change in wave length which takes place on scattering it is necessary to think of x rays as having a corpuscular as well as a wave nature. Phenomena of interference have given ample evidence that ordinary light, x rays, — in fact, all electromagnetic radiations, — have a wave nature. On the other hand it is often necessary to interpret facts by thinking of radiation as concentrated in little bundles called *photons* each photon possessing the quantum of energy which we have seen in section 109 is equal to Planck's constant h multiplied by ν the frequency.

Now Compton showed that the observed change in wave length when a primary beam is scattered can be readily explained if we treat the impact of a photon against the scattering electron in much the same way as the collision of two particles. By applying the ordinary laws of conservation of energy and of momentum, he showed that if a photon with energy equal to $h\nu$ strikes an electron (see Fig 121) the photon goes off in direction ϕ as scattered radiation with energy $h\nu'$ where ν' is less than ν while at the same time the electron goes off in direction θ with initial energy equal to the difference between $h\nu$ and $h\nu'$. This electron usually called a *recoil* electron may cause some ionization although sometimes much less than that of a photoelectron.

shorter than 0.2 angstrom, we see again the importance of scattered radiation in therapy.

For elements of high atomic weight, especially for longer wave lengths, absorption due to the excitation of characteristic rays is of greater importance than that due to scattered radiation.

116. Photoelectrons. — When the wave length of the primary beam is short enough to excite characteristic rays, there is a photoelectric emission of electrons by the radiator. These electrons are of very great importance because most of the ionization caused by a beam of x rays is due to them. What happens is this. A quantum of the incident primary radiation (if the wave length is short enough) has enough energy to eject an electron from



Courtesy C. T. R. Wilson and Royal Society

FIG. 120. A cloud-track photograph showing paths of photoelectrons when a beam of x-rays traverses a gas.

the K shell of an atom of the radiator; or alternately a somewhat longer wave length may remove an electron from the L shell; or a still longer wave length, from the N shell. In radiology we are chiefly concerned with the removal from the K shell. After the removal of the electron, characteristic rays are emitted in the way already described in section 109. The ejected photoelectron has in general sufficient velocity to ionize by collision atoms along its path.

117. Seeing Ions. — The ionization of a gas traversed by a beam of x rays is very beautifully illustrated in Fig. 120 an example of what is sometimes called a cloud expansion chamber or cloud track photograph. As we shall have other occasions where we wish to visualize the presence of ions, the basic principles employed in taking a photograph like this should be understood. Although we cannot see an ion any more than an electron it is possible by a very beautiful experiment, first performed by C. T. R. Wilson at Cambridge University to make each ion the center of a little drop of water which reveals its presence in unmistakable fashion.

suddenly falls from a high to a low value. As a first illustration consider the element tin and the graph of Fig 122, which shows how the absorption for a fixed thickness of this element changes with changing wave length. On the horizontal axis of the graph the wave length scale is in angstroms, but the scale for absorption on the other axis gives only relative values. Starting with wave length shorter than 0.1 angstrom we note that at first tin is extremely transparent, but that gradually the absorption increases until the wave length 0.424 is reached. At this critical value, a sudden drop in the absorption takes place, wave lengths just longer than 0.424 being transmitted much more readily than those just shorter. However as the wave length continues to increase, the absorption again steadily increases until at approximately 3 angstroms, there is another sudden decrease. The qualifying word "approximately

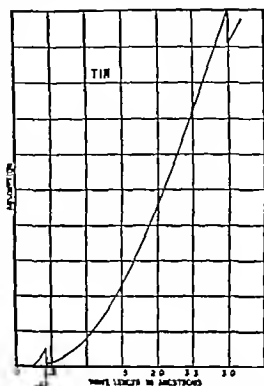


FIG. 122. Graph showing change in absorption of tin with changing wave lengths.

is used, because actually there are three sudden changes, at 2.77, 2.97 and 3.15 angstroms.

The same general phenomenon occurs if tin is replaced by copper except that the first sudden decrease in absorption does not take place until the wave length 1.38 angstrom is reached. In the graph of Fig 123 the change in the absorption of copper for wave lengths as long as 0.7 angstrom is plotted. Contrast this graph with that of Fig 124 which applies to lead. Note that for lead, the value of the first critical absorption wave length is 0.14 angstrom, a wave length right in the middle of

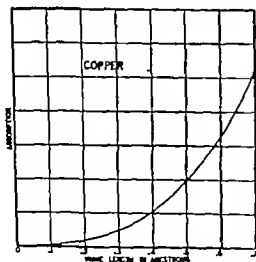


FIG. 123. Graph showing change in absorption of copper with changing wave length.

In some cloud track photographs, the ionizing paths due to recoil electrons may readily be observed

When a large number of scattering collisions take place, there are many different values of ϕ , with corresponding values of θ

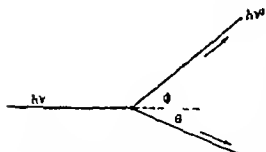


FIG. 121 An incident photon on striking a free electron is scattered in direction ϕ as a photon of longer wave length and the electron goes off in direction θ

119 Nature of Absorption.—

We are now in a position to examine a little more carefully the reason why an incident beam of x rays is reduced in intensity when passing through an absorbing layer. The absorption, which is due to the two processes we have been explaining in this chapter, is often described as *apparent* absorption, arising from scattering and *true* absorption, arising from the emission of photoelectrons. Since scattering involves a re-emission of x rays in all directions, this

means that part of the energy in the original beam is not truly absorbed by the absorbing material but rather diverted out of the original path, thus giving rise to an apparent absorption*. On the other hand, that part of the original energy which is used to liberate photoelectrons is truly absorbed. Work has to be done to pull these electrons out of the atoms, and this work is done at the expense of some of the energy of the primary beam. When absorption is dealt with quantitatively by the use of coefficients (see section 122) frequently a separate coefficient σ is used for the scattering effect and another τ for the true absorption due to the photoelectron emission.

120 Filtration and Critical Absorption Wave Length.—Reference has frequently been made to the use of filters for removing the softer components of a beam and it has been stated that, generally speaking shorter wave lengths are more penetrating than longer. This statement we must now examine a little more carefully.

For a given absorbing substance, it is only partially true to state that the longer the wave length, the greater the absorption. When absorption measurements are made over a wide range of wave lengths, it is found that as the wave length is increased, at certain critical wave lengths, the absorption

* The energy communicated to recoil electrons is a true absorption, and, in refined measurements, absorption by scattering is subdivided into apparent absorption and this true absorption.

the photon is equal to the energy needed to remove the electron. Now as the wave length of the primary beam is gradually increased, or the frequency decreased, the energy possessed by the photon becomes less and less until at a certain critical wave length, 0.424 for tin it is exactly equal to the amount needed to remove the K electron. At that stage absorption becomes a maximum. For all wave lengths longer than this critical value, the photon has not enough energy to remove a K electron, and at first there is a marked decrease in absorption since the photons in this region have far more than enough energy to remove an L electron. But once more as the wave length

TABLE XXII — SHORTEST OR K CRITICAL ABSORPTION WAVE LENGTHS FOR A FEW COMMON ELEMENTS.

Atomic Number	Element	Critical Wave Lengths
13	Aluminium	7.93 angstrom
26	Iron	1.74
28	Nickel	1.48
29	Copper	1.38
30	Zinc	1.28
47	Silver	0.485
50	Tin	0.424
74	Tungsten	0.178
78	Platinum	0.158
82	Lead	0.140

increases, the absorption gradually increases again until it reaches a maximum at a second critical value, where the energy of the photon is exactly that required to remove the L electron. Because an electron can be removed from each of the L subshells, there are the three critical absorption L values to which reference has already been made.

It is interesting to note that, if we take the K critical absorption wave length, 0.424 and calculate the corresponding voltage by means of the relation

$$\text{maximum voltage} = \frac{12354}{\text{wave length in angstroms}}$$

the value we obtain, 29.1 Kv., is exactly equal to the voltage which must be applied across an x ray tube with a tin target before the characteristic rays of this element are emitted. This agreement is due to the fact that, whether we excite the complete x ray spectrum by the impact of electrons against a target, or by the absorption of a primary beam the atom must be ionized by the removal of a K electron. In the latter case the energy utilized is that of the incident photon which, as we have already emphasized depends on the

the region used in deep therapy. It follows that a filter of lead is very undesirable, because of the high absorption of some of the very wave lengths which the operator wishes to use, that is, those just shorter than 0.14 angstrom.

In choosing a filter, therefore, care must be exercised that there is no

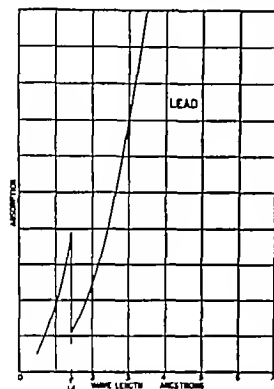


FIG. 124. Graph showing change in absorption of lead with changing wave lengths.

critical absorption wave length in the region in which the wave lengths are wanted. A glance at the values of the shortest (or K) critical absorption wave lengths given in Table XXII, will show that for the ordinary materials which may conveniently be used as filters, with the exception of lead (platinum and tungsten cannot be classed as ordinary materials), the critical absorption wave length is considerably longer than the longest wave lengths usually used in radiology. For all these elements, if we restrict ourselves to radiology uses, the shorter the wave length, the more penetrating the beam.

121 The Meaning of Critical Absorption Wave Lengths.—

In section 116 we stated that in order to have an emission of characteristic fluorescent rays, the incident photon must have enough energy to remove an electron from the K or the L or the M shells. The energy of the photon is absorbed and used to do the work of removing the electron. We have also previously pointed out that the quantum of energy possessed by a photon has the magnitude $h\nu$ where h is Planck's constant and ν is the frequency of the x ray. Suppose now we begin our absorbing experiments with an element like tin using first a wave length as short as 0.05 angstrom. The corresponding frequency is then extremely high (since the shorter the wave length the higher the frequency) and the quantum of energy possessed by the photon is far more than is necessary to remove a K electron. This photon is then not readily absorbed because we know from experiments dealing with energy exchanges of this kind that the probability of an absorption with consequent ejection of the electron is greater the more nearly the energy possessed by

through absorbing layers, equal thicknesses reduce the intensity by the same fractional amount or, alternately equal thicknesses reduce the logarithm of the intensity by equal amounts. When absorption is studied quantitatively, these ideas are utilized by adopting absorption coefficients.

The *linear absorption coefficient*, represented by μ , is, by definition, equal to the reduction per unit thickness, in the logarithm (to the base e) of the intensity. Students who have studied logarithms will perhaps recall that the natural base that is, the base which is used in the calculation of the actual numerical values found in log tables, is not 10 the common base, but the number e which is equal to the sum of a series and to ten decimal places has the value 2.7182818284. According to our definition, then,

$$\mu = \frac{\log I_0 - \log I}{x}$$

where I_0 is the original intensity and I the intensity after the beam has traversed a thickness equal to x cm. of the absorber.

To be of practical use, that is, in order that log tables may be used, we must change over to the base 10. When this is done, the factor 2.30 appears in the working formula

$$\mu = \frac{2.30 (\log_{10} I_0 - \log_{10} I)}{x}$$

A concrete example will illustrate the use of this relation. Suppose we wish to find μ , for copper for the particular wave length which is absorbed in accordance with the results given in Table XIV section 86. From this table we note that the intensity falls from an initial $I_0 = 100$ units to $I = 66.8$ units after the beam has traversed 0.50 mm. of copper. We have, then

$$\begin{aligned} \mu &= \frac{2.30 (\log 100 - \log 66.8)}{0.05} \\ &= \frac{2.30 (2.0000 - 1.8248)}{.05} \\ &= 8.06\dagger \end{aligned}$$

* This expression may also be written $I = I_0 e^{-\mu x}$

† μ can also be found using the exponential expression $I = I_0 e^{-\mu x}$. In this case $66.8 = 100 e^{-\mu \cdot 0.50}$ or $e^{-\mu \cdot 0.50} = \frac{66.8}{100} = .668$. From exponential tables μ can then be found.

wave length; in the former case, the energy is that acquired by an electron in falling through the potential difference across the tube. The two energies must be equal and that is the cause of the agreement between the values of the voltage calculated by means of the above relation and the experimental value found necessary to excite the characteristic rays. Indeed, it is not a difficult matter to derive the above relation connecting voltage and wave length, if we equate these two energies.

If the student will refer back to page 44, he will be able to write down at once that the energy acquired by an electron after falling through V volts is equal to

$$V \times 1.6 \times 10^{-12} \text{ ergs.} \quad (1)$$

Again, the energy possessed by a photon

$$\begin{aligned} &= h\nu \\ &= h \frac{c}{\lambda}, \quad \text{since frequency} = \frac{\text{velocity of waves}}{\text{wave length}}, \\ &= \frac{6.56 \times 10^{-27} \times 3 \times 10^{10}}{\lambda \text{ in centimeters}} \text{ ergs,} \\ &= \frac{19.68 \times 10^{-17}}{\lambda \text{ in angstroms} \times 10^{-8}}, \\ &= \frac{19.68 \times 10^{-9}}{\lambda \text{ in angstroms}} \end{aligned} \quad (2)$$

Equating (1) and (2) we have

$$V \times 1.6 \times 10^{-12} = \frac{19.68 \times 10^{-9}}{\lambda \text{ (in angstroms)}}$$

$$\text{or} \quad V \text{ (in volts)} = \frac{12300}{\lambda \text{ (in angstroms)}}$$

(Using more accurate values, we obtain 12354)

122. Absorption Coefficients.† — In section 86 Chapter VIII it was pointed out that when a homogeneous beam is reduced in intensity by passage

* $h = 6.56 \times 10^{-27} \text{ ergs} \times \text{sec.}$, the velocity of all electromagnetic waves $= 3 \times 10^{10} \text{ cm. per sec.}$

† Sections 122 to 125 may be omitted in a first course.

For the radiation dealt with above, that is, the beam which has a linear absorption coefficient in copper of 8.0 the mass absorption coefficient, or

$$\frac{\mu}{\rho} = \frac{8.0}{8.9} \text{ or } 0.90, \text{ since the density of copper is } 8.9 \text{ grams per cc.}$$

In standard tables it is usually values of $\frac{\mu}{\rho}$ which are given, for different substances and different wave lengths. For example, in an appendix to *X Rays in Theory and Experiment* by Compton and Allison (D Van Nostrand Co) tables are given of the values of $\frac{\mu}{\rho}$ for all the elements, for a wide range of wave lengths. A few examples taken from that book are given in Table XXIII

TABLE XXIII—VALUES OF $\frac{\mu}{\rho}$ FOR ALUMINUM, CARBON AND COPPER

Wave length	064	072	098	130	175	200	260	417
Aluminum	130	143	156	186	228	270	402	1 18
Carbon	130	136	142	152	163	175	188	256
Copper	198	232	325	57	1 12	1 59	3 25	11 4

Using these results, we note that the wave length whose absorption was dealt with in Table XIV must have a value between 0.13 and 0.175 angstrom, since its $\frac{\mu}{\rho}$ for copper is 0.90

Note that for light elements such as carbon and aluminum the values of $\frac{\mu}{\rho}$ (1) are less than those of a heavier element such as copper for correspond

TABLE XXIV— $\frac{\mu}{\rho}$ FOR A FEW ELEMENTS FOR WAVE LENGTH 0.21 ANGSTROM

Material	$\frac{\mu}{\rho}$
Paraffin	0.21
Carbon	0.176
Aluminum	0.278
Copper	1.62
Lead	5.07

ing wave lengths and (2) increase with increasing wave length much more slowly for light elements than for heavy. The first point is further emphasized by the values given in Table XXIV (taken from Compton and Allison)

Again, using a thickness of 1 mm., with $I_0 = 100$ and $I = 44.7$, we obtain

$$\begin{aligned}\mu &= \frac{2.30 (\log 100 - \log 44.7)}{0.1} \\ &= 8.04\end{aligned}$$

Or, taking one other example, since, when the thickness of absorber changes from 1.00 mm. to 1.75 mm., the intensity drops from 44.7 units to 24.5 units,

$$\begin{aligned}\mu &= \frac{2.30 (\log 44.7 - \log 24.5)}{1.75 - 1.00} \\ &= 8.01\end{aligned}$$

The homogeneous beam of rays to which the results of Table XIV apply, has, therefore, a linear absorption coefficient in copper of 8.0, and by this number its quality may be accurately described.

123 Mass Absorption Coefficient.—Of greater importance than μ , is the *mass absorption coefficient*. Suppose we compare the absorption of a homogeneous beam by water in the liquid state with the same substance in the vapor state. If we keep the cross-section of our beam constant, we find that in order to obtain equal absorption by vapor and by liquid, such a thickness of vapor must be used that the total *mass* of water is the same as in the equivalent thickness of liquid. This suggests that a coefficient more fundamental than μ is one in which we deal with the reduction in intensity per unit *mass*, for a beam of unit cross-section

$$\begin{aligned}\text{Now mass} &= \text{volume} \times \text{density} \\ &= \text{cross-sectional area} \times \text{length} \times \text{density} \\ &= 1 \times x \times \rho,\end{aligned}$$

for a beam of unit cross-section length x cm., and density ρ grams per c.c. From our definition then we can write

$$\begin{aligned}\text{mass absorption coefficient} &= \frac{2.30 (\log I_0 - \log I)}{\text{total mass}} \\ &= \frac{2.30 (\log I_0 - \log I)}{x \rho} \\ &= \frac{\mu}{\rho}\end{aligned}$$

or, in this problem

$$\begin{aligned}\frac{I}{I_0} &= e^{-14.1 \times 0.22} \\ &= e^{-3.10}\end{aligned}$$

From exponential tables, we find, as before, that $I = 0.045I_0$.

125 The Coefficients σ and τ — As we have explained in section 119 of this chapter absorption results from the two processes of scattering and photoelectric emission. The coefficient μ , therefore, is frequently separated into a scattering coefficient σ and the true absorption coefficient τ ; or, if we use mass absorption coefficients, we can write

$$\frac{\mu}{\rho} = \frac{\sigma}{\rho} + \frac{\tau}{\rho}$$

In refined measurements σ is separated into the component σ due to the apparent absorption by scattering and the component σ due to the true absorption by recoil electrons.

For light elements $\frac{\sigma}{\rho}$ changes slowly with increasing wave length, and the mean value of 0.2 in the deep therapy region gives a fair idea of its magnitude.

The value of τ on the other hand increases rapidly both with increase in wave length and with increase in Z the atomic number of the absorbing element, its magnitude being approximately proportional to $\lambda^3 Z^4$. Hence for heavy elements and long wave lengths, values of τ run into large numbers. Even for light elements, if we deal with wave lengths much longer than those encountered in deep therapy the value of τ is many times greater than σ . On the other hand for extremely short wave lengths, the scattering coefficient becomes the more important because the small value of λ^3 makes τ small regardless of the value of Z .

If we deal with a sufficiently large range of wave lengths, because of the sudden changes in the absorption at the critical absorption wave length (section 121) we have corresponding sudden changes in both $\frac{\mu}{\rho}$ and $\frac{\tau}{\rho}$. The graphs of Figs. 122, 123 and 124 were plotted from values of $\frac{\mu}{\rho}$ given in the tables in Compton and Allison's book.

It follows from the second point that, if we confine ourselves to wave lengths within the range given in Table XXIII, copper is a much better material for a filter than the other substances, because of the bigger contrast in the absorption of short and of long wave lengths.

124 A Numerical Example. — *Given a copper plate of thickness 2.2 mm, find how much it will reduce the intensity of a monochromatic beam of x-rays of wave length 0.2 angstrom, if $\frac{\mu}{\rho}$ for this wave length is equal to 1.59*

$$\begin{aligned}\text{Since } \frac{\mu}{\rho} &= 1.59 \text{ and } \rho \text{ for copper} = 8.9 \text{ (gms. per c.c.)}, \\ \mu &= 1.59 \times 8.9 \\ &= 14.1\end{aligned}$$

Let I_0 = the intensity of the beam incident on the copper plate,
and I = the emergent intensity

$$\text{Then,} \quad \mu = 2.30 \frac{\log I_0 - \log I}{x}$$

$$\text{or} \quad 14.1 = 2.30 \frac{\log I_0 - \log I}{0.22}$$

$$\text{Therefore,} \quad \log I_0 - \log I = \frac{14.1 \times 0.22}{2.30} = 1.35$$

$$\text{or} \quad \log \frac{I_0}{I} = 1.35$$

Using log tables, we find that

$$\frac{I_0}{I} = 22, \text{ or } I = 0.045 I_0,$$

that is, the emergent intensity is only about 4.5 per cent of the incident.

Using exponentials, we have the following alternative solution.

$$\mu = \frac{\log I_0 - \log I}{x}, \text{ can be written}$$

$$\frac{I}{I_0} = e^{-\mu x},$$

tain parts cannot be brought near the plate and scattering of x rays makes it impossible to obtain good results. Can the difficulty be overcome in any way?

There are two ways in which the desired improvement in contrast may be obtained (1) by diaphragming, (2) by the use of the Potter Bucky Diaphragm.

127 Diaphragms and Secondary Rays.—Diaphragming consists in limiting the aperture of the primary beam by means of an opaque filter with suitable opening. In Fig 127 for example *AB* represents a diaphragm which limits the area of the beam on the plate to *MN* whereas had a diaphragm been used of the size indicated by the dotted lines, the area would have been limited to *CD*. If now it is possible to diaphragm sufficiently

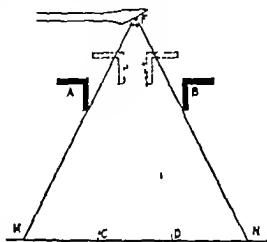


FIG. 127 Effect of diaphragm on the cone of rays

considerable improvement in the contrast can be obtained. This may best be shown by giving some experimental results of Wilsey of the Eastman Kodak Co. who made an extended study of the effects of scattered rays in radiography.

Wilsey by a simple experimental arrangement was able to compare the photographic intensity of the primary or focal beam with that of the scattered.* Using an aperture which gave a picture on the plate 20 inches in diameter, and a layer of water 6 inches thick as the scattering material, he found the intensity of the scattered radiation to be 4.9 times that of the focal beam. By diaphragming until the picture was 8 inches in diameter scattered radiation was reduced to 4 times the focal while if the picture were made 4 inches in diameter the ratio was reduced to 2. In other words, if one could conveniently use a picture 4 inches in diameter the effect of scattered rays is cut down considerably but with a scattering layer 6 inches thick the effect of scattered rays is still twice that of the direct rays from the focal spot. While some improvement, therefore is obtained by cutting down the aperture of the beam the method is limited in its application and at the best not very efficient.

128. The Potter Bucky Diaphragm.—In the Potter Bucky diaphragm, the radiographer is supplied with an arrangement which very con

Under "scattered" is also included the radiation which might be present due to rays originating at places other than the focal spot.

126. Scattered Rays and Radiography — The aim of the radiographer is to obtain a shadow picture showing good contrast and definition.

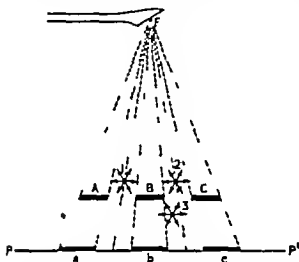


FIG. 125. Shadows of objects *A B* and *C* are not sharp because of scattered rays from such sources as 1 2 and 3.

That scattered rays, in some cases, may lessen the sharpness of the picture to such an extent as to make it of little use should be evident from an inspection of Fig 125. In this illustration *a b*, and *c* represent the shadows of three small obstacles, *A B*, and *C*, on a photographic plate or film. If scattered rays were of no importance and the focal spot at *F* were fairly small such shadows would ordinarily be sharp and the plate would show marked differences in density between the regions *a b*, and *c* and their surroundings. Suppose, however the objects *A B* and *C* are surrounded by other particles of matter (as indicated by the small dots) which scatter x rays in all directions. In that case sharp shadows would only be possible when the objects *A B C* were placed near the plate or film, somewhat as illustrated in Fig 126. If the objects are not near the film sharp shadows will no longer be possible, for two reasons. In the first place, the scattered rays from each particle such as 1 and 2 Fig 125 will cast their own shadows, and for each particle the shadow due to this cause will occupy a different position. Again scattered rays from many of the particles can pass under the objects and in this way affect the photographic plate in the region which the object shields from primary rays. For these reasons a good radiograph under such conditions would be impossible. Now whenever an operator wishes to make a radiograph of a thick portion of the body he is up against this difficulty. Cer

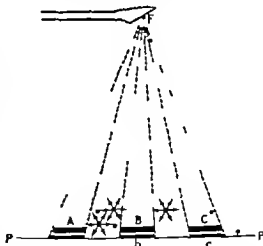


FIG. 126. Shadows of objects *A B* and *C* are sharp if objects are close to the photographic plate.

Now when the Bucky diaphragm is used and the exposure is very short, sometime shadows are observed on the photographic plate even if all the mechanical conditions such as tube position are satisfactory

One cause of these shadows arises from a very high surge in voltage which may develop in some circuits when the primary circuit is closed at an instant when the alternating current is not at its zero value. Such surges, magnified by the high tension transformer cause a momentary large tube current, and, therefore a momentary extremely intense "flash" of x rays, a beam which may be so intense as to throw a grid shadow on the plate. To prevent this type of grid shadow an arrangement, such as the Westinghouse Ignitron Timer is used to insure contact of the primary switch being made at the right instant.

A second cause of grid shadows arises if the tube current is intermittent, as it is in ordinary self rectifying units, or half wave, or full wave rectifiers (see



FIG. 129 To illustrate synchronization of grid shadows *a*, *b*, *c* and *d*

again Figs. 74 and 81) With the types of current shown in these figures, there are really a series of flashes of beams of x rays, each following the other (when the supply is 60 cycles per second) after an interval of $\frac{1}{120}$ second for full wave (Fig 81) or of $\frac{1}{60}$ cycle for self rectified or half wave arrangements (Fig 74)

Suppose an operator is taking a high speed photograph with a Bucky diaphragm. It might easily happen that the motion of the moving grid would synchronize with the flashes of the x ray beam. This would happen if the speed of the grid were such that every $\frac{1}{120}$ of a second, for full-wave or $\frac{1}{60}$ of a second for half wave, the grid moved such a distance that the shadow of the strips came in exactly the same place each flash. In Fig 129 *a b c d* represent four successive positions of the grid shadow pattern when there is this type of synchronization.

Such shadows could not possibly occur with constant potential x ray equipment, because in that case there would be no intermittent flashes, but a nearly

considerably reduces the effect of scattered rays when thick portions of the body are being photographed. The underlying principle as first suggested by Bucky is simple. Suppose, as shown in Fig. 128, a grid of lead strips, separated by narrow slots, is placed between the object to be radiographed and the photographic plate. If the lead strips are placed so that they lie lengthwise along a curve somewhat as shown in the figure, it should be evident that if the target

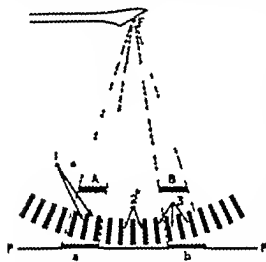


FIG. 128. Shadows of the objects *A* and *B* are cast only by rays travelling in the direction of the primary beam.

is so placed that the focal spot coincides with the intersection of the dotted lines in the figure the only rays which can get through the slots and so strike the photo plate are those in the direction of the focal beam. Secondary rays in other directions are cut off by the lead strips, as is clearly shown in the figure in the case of a few rays from particles 1, 2 and 3. Sharp shadows of objects such as *A* and *B* therefore, are cast. With a stationary grid of the kind described however such radiographs would be of little use because the shadows of the lead strips themselves would be superimposed on the picture.

In the Potter Bucky diaphragm this difficulty is overcome by adopting the simple device, suggested by Dr. Potter, of keeping the grid in steady motion throughout an exposure. By this means, since each portion of the plate is covered for the same length of time by each lead strip, the effect of grid shadows is eliminated. With such an arrangement excellent radiographs may be made of the thick portions of the body. The grid moves along a curved track and is thus always in the position to allow the passage of primary rays, while immediately above the grid a thin curved sheet of metal supports the patient.

129 Causes of Grid Shadows.—In using a Bucky diaphragm the time of exposure is increased considerably. This should be evident when it is remembered that under certain conditions the intensity of the scattered radiation may be as much as five times greater than that of the primary beam. If most of the scattered rays are removed by the grid there is a consequent increase in exposure time.

To make the time of exposure very short, as is sometimes desirable, x-ray beams of high intensities must be used, that is, the tube current must be high.

Now when the Bucky diaphragm is used and the exposure is very short, sometimes shadows are observed on the photographic plate even if all the mechanical conditions such as tube position are satisfactory

One cause of these shadows arises from a very high surge in voltage which may develop in some circuits when the primary circuit is closed at an instant when the alternating current is not at its zero value. Such surges, magnified by the high tension transformer cause a momentary large tube current, and, therefore, a momentary extremely intense flash of x rays, a beam which may be so intense as to throw a grid shadow on the plate. To prevent this type of grid shadow an arrangement, such as the Westinghouse Ignitron Timer is used to insure contact of the primary switch being made at the right instant.

A second cause of grid shadows arises if the tube current is intermittent, as it is in ordinary self rectifying units, or half wave, or full wave rectifiers (see



FIG. 129 To illustrate synchronization of grid shadows *a b c* and *d*

again Figs. 74 and 81) With the types of current shown in these figures, there are really a series of 'flashes' of beams of x rays, each following the other (when the supply is 60 cycles per second) after an interval of $\frac{1}{120}$ second for full wave (Fig. 81) or of $\frac{1}{60}$ cycle for self rectified or half wave arrangements (Fig. 74)

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Such shadows could not possibly occur with constant potential x ray equipment, because in that case there would be no intermittent flashes, but a nearly

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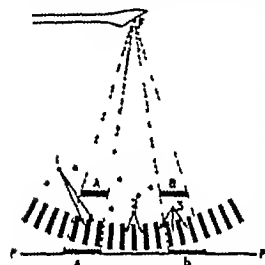


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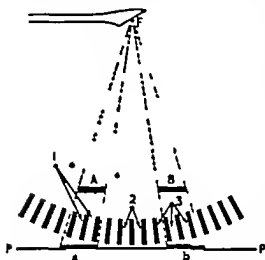


FIG. 128. Shadows of the objects *A* and *B* are cast only by rays travelling in the direction of the primary beam.

is so placed that the focal spot coincides with the intersection of the dotted lines in the figure, the only rays which can get through the slots and so strike the photo plate are those in the direction of the focal beam. Secondary rays in other directions are cut off by the lead strips, as is clearly shown in the figure in the case of a few rays from particles 1, 2, and 3. Sharp shadows of objects such as *A* and *B* therefore, are cast. With a stationary grid of the kind described, however such radiographs would be of little use because the shadows of the lead strips themselves would be superimposed on the picture.

In the Potter Bucky diaphragm this difficulty is overcome by adopting the simple device, suggested by Dr Potter of keeping the grid in steady motion throughout an exposure. By this means, since each portion of the plate is covered for the same length of time by each lead strip the effect of grid shadows is eliminated. With such an arrangement excellent radiographs may be made of the thick portions of the body. The grid moves along a curved track and is thus always in the position to allow the passage of primary rays, while immediately above the grid a thin curved sheet of metal supports the patient.

129 Causes of Grid Shadows.—In using a Bucky diaphragm the time of exposure is increased considerably. This should be evident when it is remembered that under certain conditions the intensity of the scattered radiation may be as much as five times greater than that of the primary beam. If most of the scattered rays are removed by the grid, there is a consequent increase in exposure time.

To make the time of exposure very short, as is sometimes desirable, x ray beams of high intensities must be used, that is, the tube current must be high.

CHAPTER XII

MEASUREMENT OF DOSAGE FOR ROENTGEN RAYS

131. **Quality and Intensity** — In the field of radiology x rays are used in two general ways (1) in diagnosis, either by photography or by the use of the fluorescent screen and (2) in therapy where the aim is to bring about a beneficial effect on diseased tissue. In the latter field, where the rays are an agent for treatment, it is just as important to know the dose as it is in prescribing ordinary medicines. In either case, too large a quantity may kill instead of cure the patient. It is necessary therefore to consider somewhat in detail this whole question of dosage.

First of all, it will be evident that to describe accurately a given beam of x rays two things must be known (1) its quality and (2) its intensity at any particular place in the path of the beam. We have already explained how the quality is described by giving the constituent wave lengths of the beam, or its effective wave length or the H.V.L. in some standard material. So far however although some use has been made of the idea of intensity the exact meaning of this term and its relation to dosage has not yet been discussed. The distinction between the two quantities, while simple is so important that it is worth while noting an optical illustration. Suppose a red glass is held in the path of the beam of light emerging from a projection lantern and falling on a screen. If the light inside the lantern is made brighter (as can readily be done in the case of an electric arc by increasing the current) the red spot also becomes brighter. The light falling on the screen is still red, that is, its quality is unchanged, but its intensity has been increased.

Again in sound a tuning fork may be struck very lightly so that it is difficult to hear the emitted note or it may be struck violently and heard at a considerable distance. In both cases the quality of the emitted note is the same (unless harmonics are present) in the latter case however the intensity is greatly increased.

So in x rays, we might operate a Coolidge tube always at constant voltage but in one case with low milliamperage in a second case high. The effective wave lengths in the two cases would differ but little in the second case however the intensity would be greater than in the former

steady tube current, as shown previously in Fig 85. At least one manufacturer has shown that even with a full wave generator, it is possible to attach a unit, the Grid Line Eliminator of the Westinghouse, for example, which converts the pulsating potential into constant, the capacitance of the Eliminator being such that during the exposure there is no moment when the x ray intensity falls appreciably low. This unit is such that it may be readily switched in or out, that is, so that either constant or pulsating potential is available.

130 Lysholm Grid. — Dr Lysholm has shown that it is possible to use a suitably constructed *stationary* grid. In this, absorption of scattered radiation is accomplished by exactly the same means as in the Bucky diaphragm. Although it is designed for fluoroscopic use, the manufacturer of the Lysholm grid states that it may be used with advantage in radiography because the faint shadow of the lead strips "by no means interferes with the diagnostic value of the radiograph." The grid is a light flat sheet which may conveniently be put into position and used to advantage by a radiologist whose outfit does not include a Potter Bucky diaphragm.

mental or absolute intensity as defined above the term *effective* intensity may be used, but, as this is not done in actual practice we shall not do so. It must not be forgotten, however that henceforth when we use the term intensity we are thinking of its use in this restricted sense.

134 Means of Measuring Absorbed X Ray Energy — The practical dosage problem in therapy therefore is to find in some way a means of stating that in a particular treatment so many units of x ray energy were absorbed by tissue. At the outset it may be stated that there is at present no means of measuring directly the energy absorbed by tissue. We are forced to make use of the change which x rays on absorption bring about in some purely physical medium. For example, when x rays fall on a strip of paper coated with a photographic emulsion, the rays which are absorbed cause a blackening of the paper after it is developed and the greater the amount of absorbed x ray energy the greater the blackening of the paper. Now if a beam of x rays falls simultaneously on the skin of the human body and on a piece of photographic paper the degree of blackening of the paper after development might be taken as a *measure* of the x ray energy absorbed by superficial tissue during the time of treatment. As a matter of fact, in the pioneer days of dosage, such a method was used to some extent. It has one fatal objection — along with others — and that is, that the absorption of x rays by the photographic emulsion does not change with changing wave length in the same way as absorption of tissue changes with changing wave length.

It is worth while briefly examining one or two other properties of x rays which were utilized in the attempts to establish a satisfactory means of measuring dosage. In the *pastille* method, at one time used to a considerable extent by radiologists, the dose was measured in terms of the change in color in certain salts which results from the absorption of x rays. A salt of barium platino-cyanide, for example, in the form of a round pastille some 8 mm. in diameter was exposed to the rays, the pastille being placed on a metallic sheet at a distance from the target equal to one half the distance to the patient. When in this position the absorption of a certain quantity of x rays changed the color of the pastille from the original pale green to a brownish yellow called Tint B. When rays were allowed to fall on the patient until this color change resulted a unit dose as measured this way was delivered to the patient.

At the best this method could not be more than a rough guide. More over neither this method nor that of the photographic strip gives any indication of the energy absorbed by tissue at some distance below the surface of the skin. The pastille method is also open to the same objection as was made to the use of the photographic strip. The absorption by the pastille

132. Absolute Intensity and Law of Inverse Square. — From the focal spot on the face of the target of an x ray tube a beam of x rays spreads out much the same as ordinary light rays from a small source of light. In each case energy is radiated from the source, and in each case the intensity of the beam at any point is measured fundamentally by the radiant energy which each second passes through unit area placed at right angles to the direction of the beam at this point

In either case, if no energy is lost by absorption it is not difficult to see that the intensity falls off with increasing distance according to the inverse square law. In Fig 130, all the energy which passes through the area $ABCD$ also

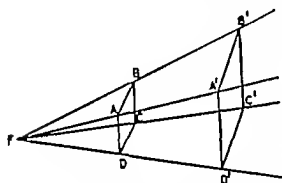


FIG. 130. If $FA' = 2FA$ then the area $A'B'C'D' = 4$ area $ABCD$

passes through the area $A'B'C'D'$, since both x rays and light rays are propagated in straight lines. Now if the distance FA' is exactly twice FA then the area $A'B'C'D'$ is exactly four times the area $ABCD$. Therefore the energy received per second per unit area at any point in $A'B'C'D'$ is one quarter of the energy received per second per unit area at any point in $ABCD$. In

other words, if we double the distance, the intensity falls to one quarter the value, or in general the intensity falls off inversely as the square of the distance from a small source, provided there is no absorption

133 Meaning of Intensity in X Ray Dosage. — When x rays are used for treatment, in general part of the x ray energy is absorbed, part is transmitted. Obviously the part which is transmitted plays no part in any beneficial or harmful effects the beam may have on tissue. The radiologist, therefore, is interested only in the portion of the beam which is absorbed by the tissue. He might, for example, have at his disposal two beams, one of strong intensity (measured fundamentally) and of extreme penetration, the other, of weak intensity and of feeble penetration. If each fell on the skin of a patient the second might have a greater biological effect than the first and if so, we might correctly say that as far as skin treatment is concerned its biological intensity was greater than that of the first beam.

In x ray dosage, we are interested in the absorbed energy only and when we use the term intensity in radiology we really are thinking of the absorbed energy per square centimeter per second. To distinguish this from funda

135 Dosage by Ionization. — The only property of x rays which can be used satisfactorily as a means of evaluating a physical dose having a direct relation to tissue dose, is the ability of a beam to ionize a gas like ordinary air. There are several reasons for this.

(1) Over a wide range of wave lengths the ionization of air is directly proportional to the x ray energy absorbed.

(2) Since tissue is largely composed of the light elements hydrogen, oxygen, carbon and nitrogen what we might call the effective atomic weights of air and of tissue do not differ to any great extent. It is useful to remember that, over a wide range of wave lengths, the absorption per gram is nearly the same for air for water, and for tissue.

(3) Closely related to (2) is the fact that the absorption of air changes with changing wave length in the same way as the absorption by tissue.

(4) It is highly probable that the primary cause either of the beneficial or of the injurious effect of x rays on tissue is due to ionization.

(5) The ionization method of measuring absorbed x ray energy lends itself to the establishment of a convenient, universal unit, which may readily be realized.

It is necessary therefore, to study in detail the whole question of ionization of air and its use in the measurement of x ray dosage.

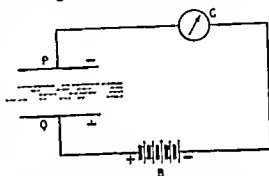


FIG. 132. A very sensitive galvanometer *G* indicates a current when a beam of x-rays ionizes the air between *P* and *Q*.

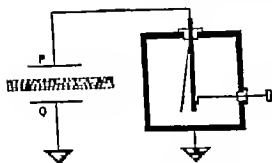


FIG. 133. A charged electroscope attached to *P* is discharged when beam of x-rays ionizes the air between *P* and *Q*.

136 Saturation Ionization Current. — Consider the two arrangements illustrated in Fig 132 and in Fig 133. In Fig 132 two plates, *P* and *Q* separated by an air gap are joined in series with

a battery *B* and a very sensitive galvanometer. In Fig 133 the plate *Q* is grounded and the insulated plate *P* is joined to the leaf of an electroscope. With the galvanometer arrangement there is normally no current because

material with changing wave length does not parallel the corresponding change in absorption by tissue

A somewhat more scientific method made use of the property which x rays have of decreasing the electrical resistance of the element selenium. Although this method, as exemplified in the *Furstenau Intensimeter*, is open to similar objections, it is worth a brief examination if only for the sake of further illustrating some of the difficulties involved in the measurement of dosage. The experimental arrangement consists essentially of a selenium cell *Se*, Fig. 131, placed in an electric circuit in series with a battery and a galvanometer. When no beam of x rays is incident on the selenium the position of the pointer of the galvanometer is marked zero. If now a beam of rays falls on the cell, its resistance alters, the current increases, and the pointer takes up a new position at which it remains, provided the intensity of the beam does not alter. If the intensity of the beam is increased, a corresponding greater deflection is indicated. Hence the galvanometer scale may be marked in arbitrary units

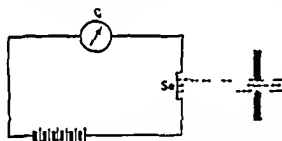


FIG. 131. To illustrate the use of a selenium cell in measuring x-ray intensities.

which are proportional to the intensity of the x ray beam or, more accurately, to the intensity absorbed by selenium

Suppose it were found that when a certain beam, whose intensity was 2 units as measured by the scale of this instrument, fell on the skin of a patient for 30 minutes a mild erythema was produced. It would

then be reasonable to state that, measured by this method, the particular dose required to cause such an erythema, is 2×30 or 60 Furstenau units. If another time, a beam of the same quality were used, but of intensity 4 units on this scale, it would be natural to assume that to produce the same biological effect, the rays would have to fall on the patient for only 15 minutes, since $4 \times 15 = 60$ units as before. But the assumption that a weak intensity for a long time has the same effect as for a correspondingly shorter time is not necessarily true, and is one that has to be justified.

Again, if the *quality* of the beam of rays was now changed and its intensity adjusted until 2 units were again recorded by this intensimeter, it would be found that the time required to produce the erythema was no longer 30 minutes. A separate calibration would then be necessary for each kind of ray

On the whole—and there are still other objections which need not be discussed—this method is not good enough for the exact measurement of dosage.

135 Dosage by Ionization. — The only property of x rays which can be used satisfactorily as a means of evaluating a physical dose having a direct relation to tissue dose, is the ability of a beam to ionize a gas like ordinary air. There are several reasons for this.

(1) Over a wide range of wave lengths the ionization of air is directly proportional to the x ray energy absorbed.

(2) Since tissue is largely composed of the light elements hydrogen, oxygen, carbon and nitrogen, what we might call the effective atomic weights of air and of tissue do not differ to any great extent. It is useful to remember that, over a wide range of wave lengths, the absorption per gram is nearly the same for air, for water, and for tissue.

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It is necessary therefore, to study in detail the whole question of ionization of air and its use in the measurement of x ray dosage.

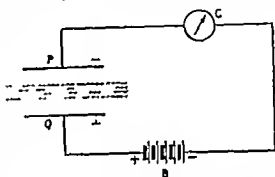


FIG. 132. A very sensitive galvanometer *G* indicates a current when a beam of x-rays ionizes the air between *P* and *Q*.

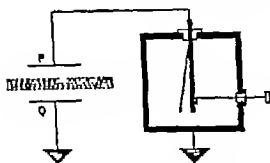


FIG. 133. A charged electrostatic electrometer attached to *P* is discharged when beam of x-rays ionizes the air between *P* and *Q*.

136. Saturation Ionization Current. — Consider the two arrangements illustrated in Fig 132 and in Fig 133. In Fig 132 two plates, *P* and *Q* separated by an air gap are joined in series with

a battery *B* and a very sensitive galvanometer. In Fig 133 the plate *Q* is grounded and the insulated plate *P* is joined to the leaf of an electrostatic electrometer. With the galvanometer arrangement there is normally no current because

for moderate voltages air is a good insulator. With the electroscope arrangement, if the insulated plate and the leaf are given a charge, the leaf remains stationary for the same reason *. Now suppose a beam of x rays, indicated by the dotted lines in these figures, traverses part of the region between the plates *P* and *Q*. The air in its path is then ionized and in the arrangement of Fig. 132, the galvanometer (if sensitive enough) indicates a current or in Fig. 133, the leaf of the electroscope falls. A steady deflection is recorded by the galvanometer, because as long as the x ray beam is in action, there is a steady stream of ions, positive to the negative plate negative to the positive. If the insulated system in the electroscope arrangement is positively charged, negative ions will go to *P* (positive to the earthed plate *Q*), and the leaf will drop at a rate which depends on the magnitude of the current of ions.

Should the beam of x rays be made more intense, a greater number of ions is formed in each unit volume, a bigger ionic current flows, and a greater

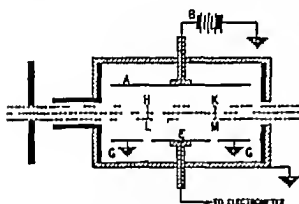


FIG. 134. The essential features of a standard ionization chamber

deflection is recorded by the galvanometer or with the other arrangement, the leaf falls at a faster rate. Hence, either arrangement provides us with a convenient means of measuring the (absorbed) intensity of an x ray beam, the first by the steady deflection of a galvanometer the second by the rate of fall of the leaf of an electroscope.

To make sure that the galvanometer deflection or the rate of fall of the leaf is *exactly* proportional to the absorbed intensity an important condition must be fulfilled, and that is, the ionization current must have its saturation value. This means that the potential difference between the plates *P* and *Q* must be large enough to remove *all* the ions as fast as they are formed. If the voltage is too small, some of the positive ions will unite with negative or to use the technical term a certain number of positive and negative ions will *recombine*. The voltage, therefore must be sufficiently high to prevent *recombination* so that as many ions reach the plates per second as are manufactured by the ionizing beam.

* Actually due to defective insulation and to a *very slight* amount of ionization present at all times in the air the leaf falls very slowly so slowly that often it can be neglected. In making exact observations it is an easy matter to correct for this *natural leak* as it is called.

In any of the arrangements we shall later describe, it is assumed that sufficient voltage is used to insure saturation

137 Ionization Chambers. — In the arrangements used practically to measure ionization currents, the plates *P* and *Q* of Fig 132 and Fig 133 correspond to what is called an *ionization chamber*. We distinguish two main kinds (1) the *standard* and (2) the *small thumb* chamber. The essential features of a standard chamber are shown in Fig 134. In this arrangement ions resulting from the passage of the beam of x rays are driven from the volume *HKLM* to the collecting electrode *E* because of the electric field maintained between the plates *A* and *E* by the battery *B* and the total charge coming to the electrode in any given time is measured by the instrument attached to *E*. Further details about the use of the standard chamber will be given presently. At this stage it is sufficient to state that it is not suitable for use by a practicing radiologist, but is used for standardization purposes.

The essential features of a simple arrangement with a thumb chamber are illustrated in Fig 135. *C* represents the chamber, which encloses a volume which may be of the order of one or two cubic centimeters. Its walls are of some light material — even paper will do — whose inner surface is made conducting by a thin coating of graphite and is grounded.

E the insulated electrode to which ions are attracted is joined to a measuring instrument, such as an electroscope or other type of electrometer by the insulated conductor *K*. This conductor is shielded from electric disturbances by surrounding it with an outer earthed tube or shield *S*. To prevent ionization in the region between *K* and the outer tube this space may be filled with an insulating material like rubber or, by means of a vacuum pump the pressure in this region may be kept so low that ionization by any radiation penetrating the shield may be neglected. If desired the tube connecting the electrode to the electrometer may be flexible and of any convenient length.

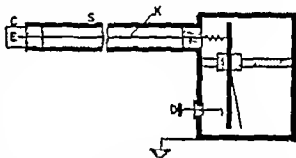


FIG. 135. Arrangement for using a small ionization chamber *C* and an electroscope.

138. The Roentgen. — Before discussing further details concerning ionization chambers, it is desirable at this stage to explain the nature of the fundamental unit in terms of which dosage is now measured.

Whatever the arrangement used to measure an ionization current, it should

for moderate voltages air is a good insulator. With the electroscope arrangement, if the insulated plate and the leaf are given a charge the leaf remains stationary for the same reason*. Now suppose a beam of x rays, indicated by the dotted lines in these figures, traverses part of the region between the plates *P* and *Q*. The air in its path is then ionized and, in the arrangement of Fig. 132, the galvanometer (if sensitive enough) indicates a current or in Fig. 133, the leaf of the electroscope falls. A steady deflection is recorded by the galvanometer, because as long as the x ray beam is in action, there is a steady stream of ions, positive to the negative plate negative to the positive. If the insulated system in the electroscope arrangement is positively charged, negative ions will go to *P* (positive to the earthed plate *Q*), and the leaf will drop at a rate which depends on the magnitude of the current of ions.

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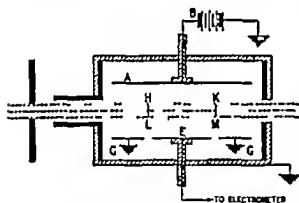


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deflection is recorded by the galvanometer or with the other arrangement, the leaf falls at a faster rate. Hence, either arrangement provides us with a convenient means of measuring the (absorbed) intensity of an x ray beam the first by the steady deflection of a galvanometer the second by the rate of fall of the leaf of an electroscope.

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In any of the arrangements we shall later describe, it is assumed that sufficient voltage is used to insure saturation.

137 Ionization Chambers.—In the arrangements used practically to measure ionization currents, the plates *P* and *Q* of Fig 132 and Fig 133 correspond to what is called an *ionization chamber*. We distinguish two main kinds (1) the *standard* and (2) the *small thimble* chamber. The essential features of a standard chamber are shown in Fig 134. In this arrangement ions resulting from the passage of the beam of x rays are driven from the volume *HKLM* to the collecting electrode *E* because of the electric field maintained between the plates *A* and *E* by the battery *B* and the total charge coming to the electrode in any given time is measured by the instrument attached to *E*. Further details about the use of the standard chamber will be given presently. At this stage it is sufficient to state that it is not suitable for use by a practicing radiologist, but is used for standardization purposes.

The essential features of a simple arrangement with a thimble chamber are illustrated in Fig 135. *C* represents the chamber which encloses a volume which may be of the order of one or two cubic centimeters. Its walls are of some light material—even paper will do—whose inner surface is made conducting by a thin coating of graphite and is grounded. *E* the insulated electrode to which ions are attracted is joined to a measuring instrument, such as an electroscope or other type of electrometer by the insulated conductor *K*. This conductor is shielded from electric disturbances by surrounding it with an outer earthed tube or shield *S*. To prevent ionization in the region between *K* and the outer tube this space may be filled with an insulating material like rubber or by means of a vacuum pump the pressure in this region may be kept so low that ionization by any radiation penetrating the shield may be neglected. If desired the tube connecting the electrode to the electrometer may be flexible and of any convenient length.

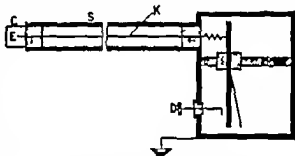


FIG. 135. Arrangement for using a small ionization chamber *C* and an electroscope.

138. The Roentgen.—Before discussing further details concerning ionization chambers, it is desirable at this stage to explain the nature of the fundamental unit in terms of which dosage is now measured. Whatever the arrangement used to measure an ionization current it should

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Whatever the arrangement used to measure an ionization current it should

be evident that its magnitude depends on two factors, (1) the intensity of the beam, and (2) the volume of air from which the ions are removed. The greater the intensity, the greater the number of ions manufactured in each cubic centimeter and, for a given intensity, the larger the volume from which the ions are collected, the greater the total number taking part in the current to the collecting electrode.

With these facts in mind, the student should be able to understand, at least in a general way, why in 1928 the Second International Congress of Radiology adopted the following definition of a physical unit, called the *roentgen*, in terms of which dosage can be measured.

The roentgen is the quantity of x-radiation which, when the secondary electrons are fully utilized and the wall effect of the chamber is avoided, produces in 1 c.c. of atmospheric air at 0°C and 760 mm. pressure, such a degree of conductivity that one electrostatic unit of charge is measured at saturation current.

In 1937, at the Fifth International Congress, this definition was altered to the form given in section 142. Since for x rays generated by means of voltages as high as about 200,000, the two definitions agree in their practical application, we shall make use of the 1928 definition in our initial discussion.

It will be recalled that the electrostatic unit of charge (e.s.u.), which we have previously designated the statcoulomb (section 35), is such a quantity that when it is placed 1 centimeter away in air from an equal quantity, the force of repulsion of one on the other is 1 dyne. In actual calculations, it is more convenient to know that the coulomb, the practical unit of quantity, is related to the statcoulomb by the equation,

$$1 \text{ coulomb} = 3 \times 10^9 \text{ statcoulombs.}$$

Suppose, in an arrangement like Fig. 134, a current of 10^{-8} ampere is recorded by the measuring device and that the volume *HKLM* in which the ions are produced is 10 c.c.

$$\begin{aligned} \text{Since } 10^{-8} \text{ ampere} &= 10^{-8} \text{ coulomb per second,} \\ &= 10^{-8} \times 3 \times 10^9 \text{ statcoulombs per second,} \\ &= 3 \text{ statcoulombs per second,} \end{aligned}$$

we may write 'The number of statcoulombs produced in 10 c.c. in 1 sec. = 3. Hence, the number produced per c.c. in 1 sec. = 0.3. According to the above definition the intensity of the beam producing the ions in the region *HKLM* is 0.3r units per second. This assumes that the air is at 0°C and 76 cm. pressure. For other temperatures and pressures, the correction referred to in section 141 must be made.

It must be clearly understood that the roentgen is a unit of quantity and that intensity has reference to the absorbed energy in unit time. If the above beam continued in operation for 10 minutes, the physical dose delivered in the region *HKLM* would be $0.3 \times 10 \times 60$ or 180r units.

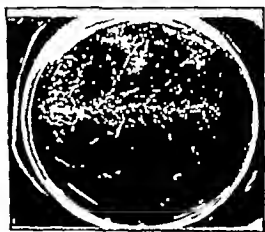
To fulfill the conditions expressed in the above definition of the roentgen certain precautions must be taken

(1) The current must have saturation value; (2) all the secondary electrons must be utilized; and (3) the wall effect of the chamber must be avoided. Let us examine each of these in turn.

(1) The meaning of saturation has already been explained and need not be further discussed.

(2) We have also previously explained that when a beam traverses a gas like air the ionization is due to the action of photoelectric and recoil electrons. Now these liberated electrons may travel outside the track of the primary beam as shown by the cloud track photograph in Fig 120. For long wave lengths the "outside" effect is slight, but if the wave length of the primary beam is made shorter and shorter the excursion of the electrons out of the track becomes longer and longer. This means that ionization often takes place well outside the actual region traversed by the primary beam. This long excursion of the photoelectrons is nicely shown in Fig 136 a reproduction of a photograph taken with tube voltage 550 Kv by Dr Walter Jordan at the California Institute of Technology and reproduced through the kindness of Dr Charles C Lauritsen. The tube voltage used when Fig 120 was taken is not available, but it is very much less than 550 Kv. If then all the ions are to be utilized — the secondary electrons fully utilized — the separation of the electrodes must be sufficient to insure that none of these electrons strike containing walls before they have used up their energy in ionizing. "For a narrow (1 cm) beam, of 200-Kv x rays a spacing of 10 cm. is sufficient." (L. S. Taylor)

In this connection the student may well ask "If ions are formed outside *HKLM* (Fig 134) is it correct, in making calculations, to use only the volume of this region? Actual practice provides the answer to this question, because



Courtesy Charles C. Lauritsen

FIG. 136. Passage of 550,000 volt x-rays through a cloud chamber. Note the long excursion of the photoelectrons.

be evident that its magnitude depends on two factors, (1) the intensity of the beam, and (2) the volume of air from which the ions are removed. The greater the intensity, the greater the number of ions manufactured in each cubic centimeter and, for a given intensity, the larger the volume from which the ions are collected, the greater the total number taking part in the current to the collecting electrode

With these facts in mind, the student should be able to understand, at least in a general way, why in 1928 the Second International Congress of Radiology adopted the following definition of a physical unit, called the *roentgen*, in terms of which dosage can be measured.

The roentgen is the quantity of x-radiation which, when the secondary electrons are fully utilized and the wall effect of the chamber is avoided, produces in 1 c.c. of atmospheric air at 0°C and 760 mm. pressure, such a degree of conductivity that one electrostatic unit of charge is measured at saturation current.

In 1937, at the Fifth International Congress, this definition was altered to the form given in section 142. Since for x rays generated by means of voltages as high as about 200,000, the two definitions agree in their practical application, we shall make use of the 1928 definition in our initial discussion.

It will be recalled that the electrostatic unit of charge (e.s.u.) which we have previously designated the statcoulomb (section 35) is such a quantity that when it is placed 1 centimeter away in air from an equal quantity the force of repulsion of one on the other is 1 dyne. In actual calculations, it is more convenient to know that the coulomb, the practical unit of quantity is related to the statcoulomb by the equation

$$1 \text{ coulomb} = 3 \times 10^9 \text{ statcoulombs.}$$

Suppose, in an arrangement like Fig. 134 a current of 10^{-8} ampere is recorded by the measuring device and that the volume *HKLM* in which the ions are produced is 10 c.c.

$$\begin{aligned} \text{Since } 10^{-8} \text{ ampere} &= 10^{-8} \text{ coulomb per second,} \\ &= 10^{-8} \times 3 \times 10^9 \text{ statcoulombs per second,} \\ &= 3 \text{ statcoulombs per second,} \end{aligned}$$

we may write The number of statcoulombs produced in 10 c.c. in 1 sec. = 3. Hence, the number produced per c.c. in 1 sec. = 0.3. According to the above definition, the intensity of the beam producing the ions in the region *HKLM*, is 0.3r units per second. This assumes that the air is at 0°C and 76 cm. pressure. For other temperatures and pressures, the correction referred to in section 141 must be made.

The second factor relates to the cross-sectional area of the beam of primary rays. This is controlled by the use of diaphragms which narrow down the primary beam and enable an exact calculation of the cross-sectional area to be made. As standard chambers are used only in standardization laboratories further details are omitted in this book.

140 Null Method of Measuring Ionization Current. — It has been stated in the preceding section that a suitable electric field is obtained in a standard chamber when both the guard plates *GG* Fig 137*b* and the electrode *E* are at ground potential. In actual use *E* is initially grounded, but this connection to earth must be broken before any measurement can be made of the charge carried to *E* by the ions, in any time interval. If this charge were measured by direct connection to an electrometer the potential would steadily change as time went on and in consequence the electric field would also change sufficiently to introduce an appreciable error in the calculated volume. To overcome such an error in laboratories such as the Bureau of Standards in Washington and the National Physical Laboratory Teddington a null method is used. Figure 138 illustrates in simple form the arrangement used in one such method. *E* it will be seen, is connected both to the measuring electrometer and to one side of a standard condenser *C* whose capacity is accurately known. The other side of the condenser is connected to a source of potential whose magnitude may be varied, the polarity being so chosen that the charge on the side of the condenser connected with *E* is opposite in sign to the charge on the ions coming up to *E*. When a measurement is being made initially the key *A* is closed thus grounding *E* and the system to which it is attached. With the x ray beam in operation *K* is then opened, and a stream of ions begins to flow to *E*. But, as *E* accumulates a charge the potential applied to the condenser is steadily altered in such a way that an equal charge of opposite sign is induced on the side of the condenser connected with *E*. The resultant charge on the system joined to the electrometer is therefore kept at zero and the indicator of the electrometer remains unchanged in position.

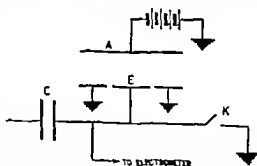


FIG. 138. By varying the voltage across the condenser *C* the ionic charge coming to *E* may be annulled, thus keeping *E* at the original ground potential.

To determine the total charge *Q* coming to the electrode in an observed

it is the volume $HKLM$ which is always used. In other words, the *cubic centimeter in the 1928 definition of the roentgen is taken to refer to the region where the electrons are liberated by the primary beam*. In this respect the wording of the 1937 is more exact. (Section 142)

(3) If x rays are allowed to strike the walls of the chamber, secondary x rays and electrons may be emitted, and these may add to the ionization of the air between the electrodes. In an actual standard chamber therefore, the primary beam is carefully isolated by protecting diaphragms, with the electrodes well separated as noted above. As a still further precaution the walls of the chamber are made of materials of low atomic weight so that if any stray radiation did strike them, the emitted fluorescent rays would be so soft (see section 106) that they would be absorbed before having produced any appreciable ionization.

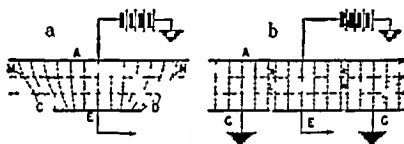


FIG. 137 By the use of guard plates G and G a uniform electric field can be maintained between A and E , as in b . In a the field is far from uniform.

139 Determination of Effective Volume.—In considering the exact value of the volume $HKLM$ to be used in calculating the number of r units, two factors are of importance. The first has to do with the nature of the electric field between the charged plate A Fig 134 and the collecting electrode E . Since charged particles move along electric lines of force, the ions in an arrangement like that shown in Fig 137*a*, move to E out of the region $MNCD$. The volume of this region varies with the relative size of the plates and is not easy to measure. For accurate calculation, the lines of force should run as nearly perpendicular as possible over the whole face of the electrode E somewhat as shown in Fig 137*b*. This is accomplished by surrounding this electrode with the grounded guard plates G and G . If initially E is also grounded, as is usually done in standard measurements (see section 140) and if the gap between E and the plates GG is narrow then the ions are drawn to E from the volume $HKLM$ whose length is equal to the distance from the center of the narrow opening on one side of the electrode to the center of the other opening.

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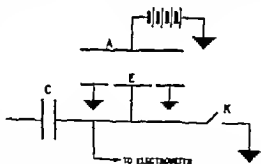


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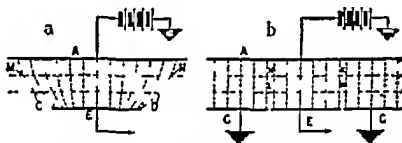


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142. 1937 Definition of the Roentgen. — At the Fifth International Congress of Radiology held at Chicago in 1937 a somewhat different definition of the roentgen was provisionally adopted in order to make this unit available for gamma rays of radium and for the ultrahigh voltage x rays now in use (See Chapter XIV) The new definition reads as follows

The roentgen shall be the quantity of x or gamma-radiation such that the associated corpuscular emission per 0.001293 gram of air produces in air, ions carrying 1 e.s.u. of quantity of electricity of either sign.

In many respects the two definitions are identical and no change need be made in the work of the preceding pages. Note, however the following

(1) 0.001293 grams is the mass of 1 c.c. of air at 0°C and 760 mm. pressure.

(2) Saturation conditions are not mentioned because the definition refers to the number of ions produced per cubic centimeter by the radiation and naturally includes all of them In making measurements, however it is just as necessary as ever to use sufficient voltage to insure that the ions do not recombine.

(3) The ions to be considered are those produced by the corpuscular emission per 0.001293 grams, that is, by the secondary electrons (photoelectric and recoil) set in motion by the primary beam This corresponds to the clause in the 1928 definition requiring the utilization of all the secondary electrons, but specifies without any ambiguity that the volume to be used in calculating the number of r units is the volume of the region in which the primary beam produces its "associated corpuscular emission" (See section 138(2))

(4) The 1937 definition specifically rules out any possible ionization by scattered x rays, a matter left uncertain in the 1928 definition. For x rays generated by voltages up to about 150 000 volts, any ionizing effect due to scattered radiation is negligible, and again for such rays one definition is as good as the other For ultrahigh voltage x rays or for gamma rays of radium scattered radiation can be of very great importance although the magnitude of the resulting ionization is difficult to measure Because the 1937 definition explicitly rules out any consideration of scattered radiation it is applicable to the measurement of roentgens for the whole range of rays. "Such measurements, for hard radiations, and for radiations in tissue is one of the problems occupying radiologic physicists at the present time It is being necessary to develop special types of ionization chambers to be sure that all the ions correctly included are measured, and that no extraneous ones are introduced. (Quimby)

time t , all that is necessary is to calculate the magnitude of the charge given to the condenser. A numerical example will illustrate the method.

The intensity of a beam of x-rays at a certain place was measured by a standard ionization chamber arranged so that the effective volume in which ions were produced was 2.51 c.c. When the collecting electrode was attached to a condenser of capacity 127×10^{-6} microfarad, it was found that the electrometer remained undeflected if at the end of 1 minute the potential applied to the condenser was changed by 9.2 volts. Calculate the intensity in r units per minute. (The volume refers to air at 0°C and 760 mm. pressure.)

$$\begin{aligned} Q &= \text{compensating quantity on condenser} \\ &= \text{capacity} \times \text{potential} \\ &= 127 \times 10^{-6} \times 10^{-4} \times 9.2 \text{ coulombs*} \\ &= 127 \times 10^{-10} \times 9.2 \times 3 \times 10^9 \text{ statcoulombs} \\ &= 3.505 \text{ statcoulombs.} \end{aligned}$$

Therefore, the number of statcoulombs collected in 1 minute, if the volume were 1 c.c.

$$= \frac{3.505}{2.51} = 1.4,$$

or, the intensity of the beam

$$= 1.4r \text{ units per minute.}$$

141 Correction for Temperature and Pressure. — When measurements are made with a standard chamber the air is not in general either at 0°C or 760 mm pressure. A correction must therefore be made for these factors. Since the absorption of x rays is directly proportional to mass, all that is necessary is to reduce the observed volume at $t^{\circ}\text{C}$. and P mm. pressure to its value under standard conditions. By application of the elementary gas laws, we can write at once

$$\begin{aligned} &V \text{ c.c. at } t^{\circ}\text{C. and } P \text{ mm pressure} \\ &= V \times \frac{273}{273 + t} \times \frac{P}{760} \text{ c.c. at } 0^{\circ}\text{C., and 760 mm.} \end{aligned}$$

In all problems given in this text, we shall assume that this volume correction has been made.

* 1 microfarad = 10^{-6} farad. An alternate method of calculating the number of coulombs is to use the relations 300 volts = 1 statvolt, and 1 microfarad = 900 000 statfarads.

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143 Thimble Chambers.—Because of its fundamental importance, detailed attention has been given to the explanation of the means of measuring in r units per second the intensity of a beam of x rays by the standard chamber. In actual practice, the radiologist or his technician makes use of the thimble type of chamber rather than a standard because by such means in a very short time he can evaluate the dose in r units or the intensity in r units per second. It should never be forgotten, however, that previously someone had to calibrate his thimble chamber with the aid of a standard.

We must now amplify the information about small ionization chambers given in section 137. To begin with it is well to note that, except in rare cases, the ionization produced per cubic centimeter in a small chamber is not the same as that produced per cubic centimeter by the same beam at the same place, in free air. There are several reasons for this. (1) Because of absorption of the primary beam by the walls of the chamber the ionization is reduced. This effect can be lessened by using chamber walls of extreme thinness, but (2) whatever the thickness, photoelectrons emitted by the wall material increase the ionization. (3) The corpuscular electrons produced within a small volume strike the walls before they have exhausted their ability to ionize.

The above factors, however, do not constitute objections to the use of thimble chambers, because as already noted, they are calibrated by means of a standard chamber. What is of great importance, is the requirement that the ionization as measured by the small chamber should be directly proportional to that measured by the standard, *over a wide range of wave lengths*. When this condition is fulfilled, the chamber is said to be of the "air wall" type as distinguished from the free-air standard chamber. Practically this result can be obtained by making the walls of the chamber of material or materials of low atomic weight, so that the mean atomic number is about the same as air. For example, to quote L. S. Taylor "it is thus possible to make a chamber having a graphite shell with aluminum collector which will give readings nearly proportional to the open air chamber over a wide wave length range of the harder radiations. Again we quote from the 1937 Recommendations of the British X-ray and Radium Units Committee "it is an experimental fact that the ionization in chambers suitably constructed and lined with certain mixtures, though not necessarily equal to the ionization produced by the same beam of radiation in air is proportional to it over a wide range of wave lengths."

In the next section details are given concerning the use of a thimble chamber in common use which is approximately "air wall."

144 Victoreen Condenser Meter — In this type of instrument the small ionization chamber *C* Fig. 139 is situated at one end of the chamber tube *T* whose other end may be inserted into a bayonet socket on the outside of the box *B*. When the tube *T* is driven home electrical connection is made between the electrode *E* in the ionization chamber and a string electrometer housed in the box *B*. This box also contains (1) a device for giving a charge to the electrometer and the attached electrode and (2) a battery to operate a small lamp which illuminates the scale of the filament of the electrometer. Neither of these is shown in the diagram. By means of the microscope *M* an observer can read the position of the image of the string of the electrometer on a scale marked in *r* units.

In using this instrument, the electrometer and the insulated system connecting it to the electrode *E* are charged until the image of the string comes to the zero mark on the scale. The tube *T* is detached from the electrometer box and a cap protecting the chamber *C* is removed, and placed on the other end of the tube. The tube is then placed with the chamber end in the path of the x ray beam at the place where its intensity is to be measured, and left there, normally for one minute. Because of the ionization in the chamber a part of the charge on the electrode *E* and the connecting conductor is destroyed. At the end of the minute the tube is reinserted in the socket, the cap being replaced over the chamber and connection is again made with the electrometer. Because of the loss of charge by the electrode system the potential of the electrometer alters when this connection is made, and the string or its image moves from the original zero reading to another part of the scale. Because of previous calibration the numbers on the scale read roentgens directly. Thus, if 15 were now read on the scale the intensity of the beam at the spot where the chamber had been placed, would be 15*r* units per minute.

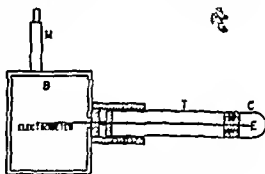


FIG. 139 In the Victoreen condenser-meter the ionization chamber *C* with attached tube *T* can be detached from the measuring electrometer.

Because of the loss of charge by the electrode system the potential of the electrometer alters when this connection is made, and the string or its image moves from the original zero reading to another part of the scale. Because of previous calibration the numbers on the scale read roentgens directly. Thus, if 15 were now read on the scale the intensity of the beam at the spot where the chamber had been placed, would be 15*r* units per minute.

By using different types of tubes and chambers condenser meters of various ranges are available. For example the Victoreen Instrument Company advertize meters reading up to 25*r*, 100*r*, and 250*r* units per minute, as well as a very sensitive one for measuring stray radiation reading only to 0.25*r* per minute. This firm states that with a single chamber measurement is possible for any wave length radiation from that produced by a standard x ray

tube at 60 Kv P up to and including gamma rays of radium, with a wave length error not exceeding 6 per cent at both extremes. A calibration curve can be supplied giving the necessary correction, if any, within 2 per cent."

Other chambers involving more or less the same fundamental principles, are available, which record the *total dose in r units* during the progress of a treatment. In the Victoreen Integrator, for example, the progress of a dose up to 300r units may be watched by means of a pointer moving over an ordinary scale. In the Hammer Dosimeter the electrical arrangement is such that every time a collecting electrode has acquired a charge equivalent to a dose of 5r units, a clock mechanism moves the hand of a dial one division, while at the same time the electrode is discharged and made ready to collect another charge.

145 Air Dose, Tissue Dose, and Back Scatter — In the preceding sections we have shown how the intensity of a beam may be measured at a specified place *in air* by an ionization chamber. In therapy, the radiologist is interested primarily in the dose delivered to *tissue* and that question we must now examine. Since it is reasonable to assume that the action of x-rays in therapy is due to the resulting ionization in tissue, and since to a first approximation ionization in tissue is the same as in an equal mass of air, tissue dosage is measured in terms of the ionization caused in a small cavity of air situated, if possible, in the midst of the region under treatment. In superficial treatment, a small ionization chamber can be placed on the skin of the patient, and the skin dose measured directly. In deep therapy, it is as a rule impossible to imbed the chamber in the tissue and the depth dose has to be found by experiments with a *phantom* that is, a medium which is the equivalent of tissue in its absorption and scattering.

The magnitude of the skin dose is not the same as that measured at the same spot with the patient removed. At this stage the student will not be surprised at that statement, but it is so important that a reference to a simple experiment is not amiss. Suppose that at a certain place in air an operator has found that the intensity of an x ray beam is 2r units per minute, and that he repeats his measurement with his ionization chamber resting on the skin of a patient, but without any other change. He finds that the second measurement indicates a greater intensity than 2r per minute. The reason for the increase has already been given in Chapter XI. The primary beam gives rise to scattered rays in the tissue of the patient, and many of these — the *back scatter* — are scattered back into the ionization chamber thus increasing the ionization. The correct skin dose must include back scatter.

Many measurements of skin dose have been made by the method given in

the preceding paragraph that is, with the ionization chamber on the skin of the patient, but the results have shown that different types of chambers do not always agree. Recently a very careful study of back scatter has been made by the radiological department of the Memorial Hospital, New York under the direction of Mrs. Edith Quimby. A chamber specially designed by Dr. Failla, head of that department, has been used and tables have been drawn up giving the correct skin dose corresponding to any air dose. Provided with such tables the practising radiologist need measure only the intensity of his beam in free air. A few actual numerical values, taken from the published work of Mrs. Quimby are given in Table XXV where the numbers give the skin dose equivalent to the delivery of 100r units in free air.

TABLE XXV—SKIN DOSE CORRESPONDING TO 100 ROENTGENS IN AIR

Quality H.V.L. in Copper	Area of Field in Sq. Cm.			
	5	25	100	400
0.035 mm.	110	117	124	128
0.3	114	124	134	147
1.0	114	124	136	149
2.0	109	117	126	136

The numbers in the table show that the skin dose equivalent to 100r units in air varies with (1) the quality of the primary beam and (2) the area of the field. For example if we use always the same area, say 25 sq. cm., the skin dose is 117 units for the softest rays, 124 for the next two more penetrating rays, but falls again to 117 for the most penetrating beam. This variation is due to change in scattering with changing quality.

On the other hand, if we use always rays of the same quality those with an H.V.L. equal to 1.0 mm. of copper for example we see that the equivalent skin dose steadily increases with increasing area, changing from 114 units for the smallest area to 149 for the largest. The increase with increasing field is due to the increased importance of scattered radiation. The larger the area, the greater the volume from which rays are scattered back to the chamber or to the area of skin under treatment. In Fig 127 if the diaphragm limiting the width of the beam to *CD* is widened increasing its width to *MN* scattered rays come to a small chamber placed over *CD* from a much greater volume than with the smaller opening and hence a greater ionization is recorded.

For the same reason, if a thin portion of the body such as a hand is treated superficially the back scatter is less for the same field, than for an area backed by a thicker portion of the body. In Table XXV the numbers are based

tube at 60 Kv P up to and including gamma rays of radium, with a wave length error not exceeding 6 per cent at both extremes. A calibration curve can be supplied giving the necessary correction, if any, within 2 per cent."

Other chambers involving more or less the same fundamental principles, are available, which record the *total* dose in *r* units during the progress of a treatment. In the Victoreen Integrator, for example the progress of a dose up to 300*r* units may be watched by means of a pointer moving over an ordinary scale. In the Hammer Dosimeter, the electrical arrangement is such that every time a collecting electrode has acquired a charge equivalent to a dose of 5*r* units, a clock mechanism moves the hand of a dial one division while at the same time the electrode is discharged and made ready to collect another charge.

145 Air Dose, Tissue Dose, and Back Scatter — In the preceding sections we have shown how the intensity of a beam may be measured at a specified place *in air* by an ionization chamber. In therapy, the radiologist is interested primarily in the dose delivered to *tissue* and that question we must now examine. Since it is reasonable to assume that the action of x rays in therapy is due to the resulting ionization in tissue and since to a first approximation ionization in tissue is the same as in an equal mass of air, tissue dosage is measured in terms of the ionization caused in a small cavity of air situated, if possible, in the midst of the region under treatment. In superficial treatment, a small ionization chamber can be placed on the skin of the patient, and the skin dose measured directly. In deep therapy it is as a rule impossible to imbed the chamber in the tissue and the depth dose has to be found by experiments with a *phantom*, that is, a medium which is the equivalent of tissue in its absorption and scattering.

The magnitude of the skin dose is not the same as that measured at the same spot with the patient removed. At this stage the student will not be surprised at that statement, but it is so important that a reference to a simple experiment is not amiss. Suppose that at a certain place in air an operator has found that the intensity of an x ray beam is 2*r* units per minute and that he repeats his measurement with his ionization chamber resting on the skin of a patient, but without any other change. He finds that the second measurement indicates a greater intensity than 2*r* per minute. The reason for the increase has already been given in Chapter XI. The primary beam gives rise to scattered rays in the tissue of the patient, and many of these — the *back scatter* — are scattered back into the ionization chamber thus increasing the ionization. The correct skin dose must include back scatter.

Many measurements of skin dose have been made by the method given in

29 units. In all cases, a somewhat greater depth dose is delivered at the same depth in the case of the longer target distance. Since the greater the percentage of the surface dose delivered at the diseased tissue, the less the absorption by the intervening tissue it is obviously an advantage to have as high a percentage depth dose as possible. Now calculations based on the inverse square law as well as the numbers in the above table show that the greater the target-skin distance, the higher the percentage of the depth dose at any given distance below the surface. It is, therefore a distinct advantage to use large target-skin distances. On the other hand the greater this distance, the smaller is the intensity of the x ray beam and hence the longer the

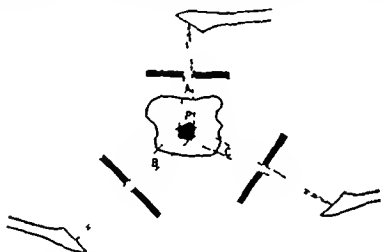


FIG. 140. To illustrate the method of cross-fire treatment.

time it takes to build up the required number of roentgens that is, the longer the time of treatment in deep therapy. In choosing the most favorable target distance, a compromise must be made between the gain arising from the increase in percentage depth dose, and the loss due to increased time of treatment. In this connection we again quote Mrs. Quimby. From a practical point of view this increase in time is an important economic factor. From a biological aspect it introduces complications because of differences in tissue recuperation. And, again, "it is not advantageous to use distances greater than ten or twelve times the known depth."

A second and more important method of reducing the absorption by the skin and intervening tissue in deep therapy consists in using *cross fire treatment*. The principle of this method is simple and will be clear after a glance at Fig. 140 where *P* represents a diseased region within the body treated through three ports of entry at *A*, *B* and *C*. If the desired dose is delivered in three

on the assumption that there is enough underlying material to give maximum back scatter

146 Depth Dosage.—In therapy, the problem is generally that of treating diseased tissue below the skin. There are then two important problems (1) how to effect a cure without injuring the skin and the healthy intervening tissue; and (2) how to measure correctly the *depth dose* delivered to the diseased tissue. We shall consider the second problem first.

As already briefly mentioned, depth dose is measured indirectly by using *phantoms*, that is, materials equivalent to tissue in their absorption and scattering of x rays. Water, rice, a mixture of rice and flour, ground meat, Columbia wax, and pressed wood are all examples of fairly good phantoms. In taking the readings given in Table XXV, the special ionization chamber used by Mrs. Quimby was backed by a mixture of rice and flour. Similarly in evaluating the depth doses given in Table XXVI, results also due to Mrs. Quimby, the chamber was embedded in a phantom of this kind. In this connection we quote Mrs. Quimby, "It is important that measurements used for determining tissue doses shall have been made in phantoms comparable in size with the part of the body undergoing treatment. The use of data obtained with large phantoms to specify doses in smaller portions of the body, such as the limbs or neck, may introduce errors because of the difference in the actual amounts of scattering materials in the two cases."

TABLE XXVI—NUMBERS OF ROENTGENS DELIVERED AT VARIOUS DEPTHS, FOR 100 ROENTGENS IN AIR. QUALITY OF RAYS GIVEN BY H.V.L. 1.0 MM. IN COPPER

	5 sq. cm.		25 sq. cm.		100 sq. cm.		400 sq. cm.	
Depth	50 cm.	70 cm.	50 cm.	70 cm.	50 cm.	70 cm.	50 cm.	70 cm.
0	114	114	124	124	136	136	149	149
1	95	96	115	116	133	134	150	152
5	43	46	61	65	82	87	108	114
10	17	19	26	29	41	45	61	67
15	6	7	11	13	22	25	33	38

The measurements recorded in the above table were taken using 200 Kv., constant potential rays, with a H.V.L. equal to 1 mm. copper after being filtered with 0.5 mm. of copper. The 50 cm. and 70 cm. at the top of alternate columns give the distance from the target to the skin (or surface of phantom). It will be noticed that at the same distance below the surface the values of the depth doses are different for different target distances. At 10 cm. depths, for example, with the 25 sq. cm. field, the doses are 26 and

TABLE XXVII — AVERAGE VALUES IN ROENTGENS ON THE SKIN OF THE THRESHOLD ERYTHEMA DOSE FOR FOUR QUALITIES OF X-RAYS

Quality	T.E.D	Absorption by the First Millimeter of Superficial Tissue
0.17 angstrom	965	18
0.22	800	17
0.27	640	16
0.42	425	16

The results of the last column were calculated using absorption coefficients $\left(\frac{\mu}{\rho}\right)$ for water and show to quote Dr Hudson that the difference in dose necessary for an erythema at the various wave lengths is due chiefly to the difference in absorption by the tissue and that the total energy absorbed in the superficial layers of skin is practically constant.

148. Specifications of Treatment Conditions. — Much more might be said about the important question of dosage but it is hoped that enough has been given to make clear the important underlying physical principles and to enable the radiologist to build on the foundations which have been laid in this chapter. To sum up we conclude with an extract from the recommendations of the International Committee for Radiological Units at the 1937 meeting

The specifications of treatment conditions shall include the following

- I. *Quantity* — The quantity of radiation (expressed in roentgens) estimated to have been received by the lesion
- II. *Quality* — (a) The spectral energy distribution of x radiation shall be designated by some suitable index, called quality. For most medical purposes it is sufficient to express the quality of the x radiation by the half value layer in a suitable material. Up to 20 Kv (peak) cellophane or cello; 20–120 Kv (peak) aluminum; 120–400 Kv (peak) copper; 400 Kv (peak) up tin. For a more definite specification of the quality of the radiation the complete absorption curve in the same material is preferable. (b) Material and thickness of filter including tube walls. (c) Target material
- III. *Technic* — (a) Total quantity of radiation per field (incident and emergent) received in an entire course of treatment. (b) Quantity of radiation per field measured at the surface (*D*) at each individual irradiation

parts, one through each port, the absorption by healthy tissue is reduced about one third.

147 Threshold Erythema Dose. — In deciding to what extent it is safe to irradiate the skin, a knowledge of the biological action of the skin to x rays is necessary. In this connection much use is made of the *threshold erythema dose* (T.E.D.), or the quantity of x radiation which produces a mild skin erythema.* This biological unit has played an important part in the development of x ray dosimetry, because, whatever the physical method used to measure a quantity of x radiation, it has always been necessary to know something of a corresponding biological action. Thus, in the pastille method of dosage, Tint B corresponded to a unit skin dose; in the method of estimating quantity by the blackening of a strip of photographic paper 10x arbitrary units corresponded to this unit; and so on for the other early methods. Now that dosimetry has advanced to the stage where the roentgen is the universal unit, all that is necessary is a knowledge of the T.E.D. in roentgens. Since a much greater fraction of the radiation delivered at the skin is absorbed by the layer of tissue just below the surface when the x ray beam is soft than when it is hard, the value of the T.E.D. depends on the wave length. As its value also depends on the area radiated (that is, on the amount of back scatter) and to some extent on the individual patient it cannot be given with the accuracy of a physical constant. Some idea of its magnitude, however, is given by the following. Using 200 Kv rays, at constant potential, with H.V.L. equal to 1 mm. of copper with a field of 100 sq cm, and with radiation given at a fairly high intensity in one setting, Mrs. Quimby gives the value of the T.E.D. as 500r units in air or 680r units on the skin. Dr J. C. Hudson, of the Collis P. Huntington Memorial Hospital, Boston after an examination of a number of radiology centers in the New England States, reports the numbers given in Table XXVII as the value of the T.E.D. for four different qualities of rays, and with an area of 100 sq cm.

* Mrs. Quimby gives the following definition. "We define our threshold, erythema dose as that amount of radiation which, delivered at a single sitting will produce in 80 per cent of all cases a faint but definite reaction, and in the other 20 per cent no visible change. We used to say within two or three weeks, but we find that the proper time interval depends on the quality of the radiation. Three or four weeks is right for 200 kv; for lower voltages a shorter time is sufficient, but for gamma rays it may be six weeks. The reaction may never be red, but appear as a tanning. The term *erythema reaction* is not a good one; I prefer to call it threshold reaction, without including the term erythema. If you insist that redness shall appear first, the question becomes very complicated."

CHAPTER XIII

RADIOACTIVITY

149 **The Discovery of Radioactivity** — The middle of the last decade of the nineteenth century was one of the most fruitful periods in physical science which has ever existed. Within two or three years, the electron, x rays, and radioactivity were all discovered. These were by no means independent discoveries because in science, as in life, one thing often leads to another. A good example of this is found in the discovery of radioactive substances. The walls of gas x ray tubes strongly fluoresce and in the early days it was not unnatural to associate the origin of these invisible rays with the fluorescence. With this idea in mind Becquerel, a French scientist, tried to see if certain compounds of the element uranium would emit x rays after being made to fluoresce by exposure to light. He was rewarded by finding an invisible radiation but was soon able to show that it had nothing to do with x rays. The uranium compound in its normal state, that is, without any stimulus by light or by anything else, was found to emit something which passed through a sheet of black paper and affected a photographic plate behind the paper. This emission moreover was perfectly spontaneous. Neither heat nor cold could start or stop it. It was a natural property of the compound.

This original discovery was followed by rapid developments and it was not long before it was found that residues of pitchblende, one of the ores in which uranium is found, were much more radioactive than pure uranium compounds themselves. Soon afterwards Madame Curie, the Polish wife of a French physicist, with the assistance of her husband, isolated polonium and radium, two substances possessing radioactive powers in a remarkably high degree. Radium was shown to be an element of atomic weight 226 with chemical properties similar to the stable element barium.

It is, however, with the nature of the radiations emitted by a radioactive substance that we are specially concerned, not with its chemical properties. The radiations, whatever they are, have three outstanding properties. They ionize the air or any gas, through which they pass; they affect a photographic plate like light or x rays or positive rays; and they cause fluorescence when they strike certain substances. The ionization effect will detect such a small quantity of radioactive substance that it has been of great importance through

diation. (c) The dosage rate expressed in r/min during each individual irradiation. (d) The total time over which a course of treatments is spread. (e) The time interval between successive doses. (f) The target-skin distance. (g) The number, dimensions, and location of the ports of entry "

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out the whole development of the subject; the photographic effect led to Becquerel's discovery; and the ability of the rays to excite fluorescence is probably familiar to most people because of the radium-coated watch hands which may be seen in the dark.

150 The Nature of the Radiations. — In seeking to find out the nature of the radiations emitted by a substance like radium, it was natural that early investigators should examine what happens when the rays traverse a magnetic field. The deflection of cathode rays by a magnetic field had shown that they were negatively charged particles. What did such a test show when

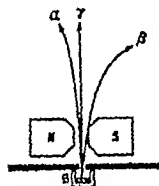


FIG. 141 A magnetic field separates the radiations from radium into three groups. The deflection of the β beam is towards the observer, of the α beam away from him.

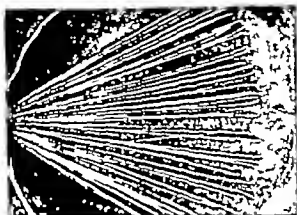
radioactive radiations were examined? In principle the experiment is extremely simple. A narrow beam of rays emerging through the top of a containing box *B* Fig 141, passes through a magnetic field between *N* and *S*. By such a means the original beam is separated into three components (1) a portion undeflected by even the strongest magnetic field; (2) a second part readily deflected in the direction which indicates that it must consist of negatively charged particles and (3) a third part, consisting of positively charged particles, deflected a slight amount in the opposite direction by sufficiently strong fields. The positive particles are called *alpha* rays, the negative *beta*, and the undeflected beam, which is of a non corpuscular nature, *gamma* rays.

Once we know that we are dealing with a flight of particles, certain questions at once suggest themselves. What is the mass of each of these particles? What charge do they carry? How fast do they move? How penetrating are they? As always, experiment provides the answer to these questions. In the following sections, important details are given concerning each kind of radiation.

151 Alpha Rays. — (1) As already noted, alpha rays are positively charged particles. Experiment shows that the magnitude of the charge carried by each particle is equal to two electronic units, that is, it is exactly twice the charge on a proton.

(2) Measurements of the amount of the deflection produced by magnetic and electric fields (see section 35) combined with a knowledge of the magnitude of the charge, show that each alpha particle has a mass about four times that of a hydrogen atom. Combining (1) and (2) we see that this particle is essentially an atom of atomic weight 4 and atomic number 2.

(3) Alpha rays cause intense ionization as they traverse a gas. This is beautifully shown by cloud track photographs (see section 117) such as are reproduced in Fig 142 and Fig 143. In Fig 142 each white line represents the path of a single alpha particle. In its flight it causes such intense ionization that the little droplets formed on ions are so close together that they give rise to an unbroken continuous streak of light.



Courtesy V. Fowler and the Royal Society

FIG. 142. Cloud track photograph showing a shower of alpha particles ejected from a small source.

The photograph of Fig 143 shows the tracks of but two alpha particles. In the left hand track of this figure it will be noted that the path turns through a small angle to the right, and then just before the end of the track, makes a second and much sharper turn to the left. These sudden turnings are evidence of the near approach of the alpha particle to the nucleus of an atom. Ordinarily this heavy particle ploughs along without being deflected out of its path even when passing right through an atom. Occasionally however the particle in its passage through the atom passes so near the nucleus that its direction is altered as shown in the photograph. The study of such deflections, that is of *scattering* when alpha rays strike a thin sheet of gold led to estimates of the size of the nucleus, and to the picture of the atom we have given in section 36.

On rare occasions an alpha particle strikes a nucleus "head-on," and in such cases things happen as we shall see later. (See section 161.)

(4) When they strike certain substances, alpha rays cause marked fluorescence, a property which is made use of in the spintharoscope one of the early radioactive toys. In this arrangement, a speck of radioactive material is placed near a screen coated with zinc sulphide and, with eyes rested, the screen is viewed through a magnifying glass in a darkened room. Little flashes of

light are seen to dance about in irregular fashion, somewhat as if in a patch of the sky the stars kept disappearing in one place and reappearing in another.



Courtesy C. T. R. Wilson and the Royal Society

FIG. 143. Cloud track photograph of paths of two alpha particles.

Each scintillation corresponds to the impact of an alpha particle on the screen. We have called this a toy but, as a matter of fact it was the basis of more than one investigation in which the number of alpha particles leaving a source in a given time was counted, and it was used with success in determining how far both alpha particles and protons travel before they are no longer able to ionize.

(5) Alpha rays have a speed which varies with the radioactive source from which they are emitted, but for the most part is between one fifteenth and one tenth of the velocity of light. In Fig. 142 it will be noted that the tracks come to an abrupt end. This is due to the fact that once the velocity falls below a certain value, an alpha particle is no longer able to ionize. The actual range in air over which they can ionize is only a few centimeters, never more than 8.6 cm.

(6) It follows from this that alpha rays are readily absorbed by solids. They are completely cut off by a sheet or two of ordinary paper or by a thickness of about 0.006 cm. of aluminum and they cannot get through 0.1 mm. of epithelial tissue. It will be evident, therefore, that if a radioactive substance is enclosed in a glass tube (unless extremely thin), alpha rays will not get through the glass.

To examine the alpha ray emission from a substance, an electroscope of the type shown in Fig. 144 is used. The insulated rod of an electroscope extends, through insulating material, into the lower chamber where it is attached to a disc *D*. The radioactive material, placed on the earthed platform, gives off radiations which ionize the air in its vicinity. When the electro-

scope is charged, the leaf falls at a rate which is proportional to the amount of ionization, and hence to the quantity of radioactive material.

152. Beta Rays. — (1) Beta rays are nothing but high speed electrons shot out of radioactive substances with velocities which cover a wide range but may exceed nine tenths of the velocity of light. To acquire a speed equal to the fastest beta ray — over ninety nine per cent of the velocity of light — a cathode ray would have to fall through a potential difference of over three million volts.

(2) Beta rays ionize a gas, although not so intensely as alpha rays. The difference will be evident by a comparison of Fig 145 with either Fig 142 or Fig 143. In Fig 145 the straight line of tiny dots marks the path of a beta ray

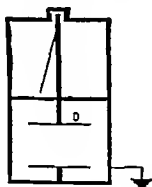


FIG. 144. An alpha ray electroscope.

moving so quickly that it is not deflected out of its path. On the same photograph the curved irregular path near the middle is due to a slow electron which is easily turned aside by collisions. The student should also examine Fig 168 where the photograph shows very beautifully the curved path of an ionizing particle like a beta ray or an electron when it is constantly deflected by the presence of a magnetic field.

(3) Beta rays, being of small mass and of high speed, are much more penetrating than alpha rays. The fastest will pass through several millimeters of a low density metal or of tissue, and traverse as much as ten feet of air before they are stopped. They are, however completely stopped by less than



Courtesy C. T. R. Wilson and the Royal Society

FIG. 145 Cloud-track photograph of a fast beta ray. The irregularly curved line of dots arises from a slowly moving electron.

light are seen to dance about in irregular fashion, somewhat as if in a patch of the sky the stars kept disappearing in one place and reappearing in another.



Courtesy C. F. R. W. Röntgen and the Royal Society

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scope is charged, the leaf falls at a rate which is proportional to the amount of ionization and hence to the quantity of radioactive material.

ample, if we wish to know the reduction in intensity of gamma rays from radium caused by a layer of 2 cm. of brass, we write down at once

$$\begin{aligned}\text{Fraction absorbed} &= 0.020 \times 20 \\ &= 0.40\end{aligned}$$

That is 40% is absorbed or 60% transmitted.

(3) Gamma rays ionize a gas through which they pass. This ionization is largely due to an emission of *secondary beta rays* which results whenever gamma rays traverse matter. Secondary beta rays may have velocities high enough to enable them to traverse several meters in air or a few millimeters in tissue before being stopped. This means that, when a radium salt is enclosed in a tube like platinum of sufficient thickness to absorb completely the original beta rays, that is, the *primary* betas, the gamma rays will cause an emission of secondary betas from the platinum. In radium therapy it is therefore necessary to surround the metal with a secondary filter of such a material that it absorbs the objectionable secondary betas, and does not emit intense secondary beta rays itself. For this purpose a material like rubber has been used to a considerable extent, although recently Quimby and co-workers have shown that "the secondary radiation is considerably less for substances of intermediate atomic number than for those toward either end of the atomic scale. Stainless steel or nickel, for example, are sometimes more suitable than rubber or celluloid.

(4) When gamma rays traverse matter a certain amount of scattering takes place, the amount depending on the quality of the primary beam and on the scattering material. The reduction of intensity when a primary beam traverses a layer of matter such as the walls of a metal tube containing radium is due in part to scattering in part to true absorption corresponding to the emission of secondary beta rays. The absorption coefficients given in Table XXVIII take into consideration both of these factors.

If a beam of gamma rays is used for the treatment of deep-seated tissue the scattered rays from surrounding tissue add to the dose delivered to the region under treatment, or in this case the effect of those scattered rays is to reduce the apparent absorption of the primary beam.

154 Radium in Treatment.—In therapy radium is used in three important ways. (1) A small amount of a radium salt is enclosed in a tiny tube or needle made of such metals as steel, monel, platinum, platinum-iridium and gold. Although radium can be obtained in the metallic state normally it is used as a salt in the chloride, bromide, or sulphate state. This needle, or a

0.5 mm. of gold or of platinum, or by about 0.4 mm. of steel or metal.* It will be seen then, that, by placing a radioactive substance in a suitable container it is not a difficult matter to remove both beta and alpha rays.

153. Gamma Rays. — (1) Gamma rays are electromagnetic waves of the same nature as x rays, but for the most part of shorter wave length. The actual values of emitted wave lengths depend on the radioactive source, and for a given source more than one wave length is emitted. From radium C, for example (see section 160), there are waves as long as 0.2 angstrom, a value in the therapy x ray range, and as short as 0.0056 angstrom.

(2) Some gamma rays are so penetrating that a thickness as great as 10 cm. of lead will not completely absorb them. A thickness of platinum or of gold equal to 0.5 mm., which we have seen completely absorbs beta rays, absorbs only about 7 per cent of the gamma rays emitted from a salt of radium enclosed

TABLE XXVIII — ABSORPTION COEFFICIENTS FOR GAMMA RAYS FROM RADIIUM

Substance	Coefficient
Aluminum	0.007
Lead	0.088
Platinum	0.139
Gold	0.140
Wood	0.021
Brass	0.020
Muscle	0.0024
Epithelial tissue	0.0024
Bone	0.0055
Water	0.0026
Paraffin wax	0.0022

in a tube. Muscular tissue, 2 cm. in thickness, reduces the intensity only 5 per cent, and even after traversing 20 cm. the rays emerge with over 60 per cent their original intensity.

As with x rays, the actual absorption coefficient varies with the wave length but an average value enables the radiologist to estimate with sufficient accuracy for most purposes the absorption caused by various materials. In this connection the numbers given in Table XXVIII† are useful.

In using the coefficients given in this table, neither logarithm nor exponentials are necessary because the fraction *absorbed* can at once be written down as equal to the coefficient \times the thickness of material in millimeters. For ex

* For exact examination of the penetration of beta rays, use is made of absorption coefficients, and the relation $I = I_0 e^{-\mu x}$ as in x rays. See section 86.

† Taken from Radium Dosage, Bulletin No. 17 of the National Research Council of Canada. By G. C. Laurence.

Standard and it should be accompanied by a certificate which reads like the following one

This certifies that the above described needle has been compared with the standards of the National Research Laboratories, and found to emit gamma radiation equivalent to x milligrams of radium in equilibrium with its disintegration products and contained in a Thuringian glass tube 0.27 mm. thick.

Note that comparison between the specimen and the National Standard is made by using gamma rays only. This is readily done by using an electro-scope with a lead wall of sufficient thickness to absorb completely all beta rays falling on it. The specimen to be measured and the standard are placed successively at the same distance from the electro-scope, and in each case the rate of discharge measured. The two quantities of radium, as measured by gamma ray emission are then in direct proportion to the rates of discharge, corrected in the usual way for natural leak.

The meaning of the phrase 'in equilibrium with its disintegration products' is explained in section 159

156. Dose in Roentgens.—In gamma ray therapy doses are now expressed in roentgens. Measurements by a number of different experimenters, using air wall chambers, indicate that for present medical purposes the quantity of gamma radiation received in one hour at a distance of 1 cm. from a point source containing 1 milligram of radium element surrounded by 0.5 mm. platinum may be regarded as approximately equivalent to 8 roentgens. (Proposals of British X Ray and Radium Units Committee 1937) If no correction is made for wall thickness, the number of 9 may be used to estimate the approximate dose. Stated otherwise the above means that an estimate of the dose in r units, uncorrected for absorption or for finite size of needle or of number of needles in an applicator may be made with fair accuracy by the following relation

$$\text{Dose} = \frac{9 \times \text{milligrams of radium} \times \text{time in hours}}{(\text{distance in centimeters})^2} \quad \text{roentgens.}$$

For example, for a 10 mg. needle used for 2 hours, the dose at 5 cm. from the source is $\frac{9 \times 10 \times 2}{25}$ or 7.2 roentgens. If the needle is surrounded by 0.5 mm. of gold, by using the coefficient 0.14 for gold given in Table XXVIII we see that the dose when corrected for absorption by the gold, is $(1 - 0.5 \times 0.14)$ or 93 per cent of 7.2. If the 5 cm. distance is all tissue, not air there is a further reduction of $(1 - 0.0024 \times 50)$ or 88 per cent.

pack consisting of a group of several needles, is then used as a source of radiation. Usually the filtration is sufficient to restrict the rays to gamma only, but with thin walls some primary betas can emerge. As already noted secondary betas emerging from the metal container can be removed by additional filtration.

The amount of radium used in a single needle is of the order of a few milligrams. An applicator may be placed in contact with the tissue, or, if sufficiently powerful at a few centimeters from it.

(2) In *radium beam therapy* the source is a bomb containing several grams of this radioactive element. In this case the patient, or more accurately the tissue under treatment, is subjected to an intense beam of gamma rays.

(3) Needles or *seeds* of *radon* or *radium emanation*, a radioactive gas manufactured by radium, are frequently used instead of the original radium salt. Small glass tubes containing the radon may be embedded or *implanted* in the actual tissue under treatment, or they may be placed within metal containers like the needles mentioned above. The difference between the use of radon and radium salt is explained below.

155 Strength of a Radium Source. — When radium needles are used, the dose delivered to the region treated depends on several factors: (1) the time of application; (2) the distance of the source from the diseased tissue; (3) the amount of absorption by the materials enclosing the radium salt and by tissue; and (4) the total quantity of radium sealed in the tube, that is, on what we may call the strength of the source.

The strength of the source is expressed in milligrams of radium, and it is measured by direct comparison with a standard. In 1912 a tube containing 16.74 milligrams of radium in the form of radium chloride, prepared by Madame Curie, was adopted as an international standard by a Committee of the Congress of Radiology and Electricity. This is kept in the International Bureau of Weights and Measures at Sèvres, near Paris. National secondary* standards have been made by comparison with the international standard, and are in the possession of such institutions as the National Physical Laboratory in England, the Bureau of Standards in Washington, and the National Research Laboratories in Canada. When a radiologist buys a radium needle its strength has been found by comparison with a National

* In addition to the important U. S. standard, a series of substandards have been recently prepared under the direction of the Committee on Standards of Radioactivity of the National Research Council of the United States. These standards have been or will be deposited at the Bureau of Standards in Washington and are to be used as working standards for investigators who may desire them.

Standard and it should be accompanied by a certificate which reads like the following one

This certifies that the above described needle has been compared with the standards of the National Research Laboratories and found to emit gamma radiation equivalent to x milligrams of radium in equilibrium with its disintegration products and contained in a Thuringian glass tube 0.27 mm. thick.

Note that comparison between the specimen and the National Standard is made by using gamma rays only. This is readily done by using an electro-scope with a lead wall of sufficient thickness to absorb completely all beta rays falling on it. The specimen to be measured and the standard are placed successively at the same distance from the electro-scope and in each case the rate of discharge measured. The two quantities of radium as measured by gamma ray emission are then in direct proportion to the rates of discharge corrected in the usual way for natural leak.

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For more accurate work, especially where a number of needles are combined in different arrangements to make applicators of different shapes, there are available dosage tables which a radiologist can consult.

Before leaving this question of dosage, we again quote from the Recommendations of the 1937 International Congress of Radiology "The specification of the conditions of gamma ray treatments should, where possible, include statements of —

- I *Quantity* — The total quantity of radiation (expressed in roentgens) estimated to have been received by the lesion.
- II *Particulars of Radium Source* — (a) The total amount and nature of radioactive substance employed (expressed as equivalent mgm. of radium element) (b) Type, number, and distribution of the containers. (c) The material and thickness of filters and the nature of the material externally adjacent to the skin
- III *Technic* — (a) In the case of surface applicators, or 'large radium units,' the quantity of radiation per field at the surface. (b) The dosage rate during each individual irradiation (c) The total time over which a course of treatments is spread. (d) The time intervals between successive irradiations. (e) In the case of surface applicators or large radium units, the radium-skin distance. (f) The number, dimensions, and situations of the ports of entry'

157 *Radon*. — Suppose a radium salt is heated and the occluded gases collected and sealed in a tube; or alternately that a solution of radium chloride in dilute hydrochloric acid, which has stood for some time is boiled and that the gases driven off are collected. It is found, by testing with an electro-scope, that the tube containing the gases is strongly radioactive. If measurements of the ionization are made every hour by a gamma ray electro-scope, it is noticed that at first the activity of the tube increases until, after some five hours, it has reached a maximum. Thereafter if the tube is examined every 24 hours for a succession of days, it is found that its radioactivity steadily becomes less and less. The numbers given in Table XXIX show the rate at which the tube loses its radioactivity

It should be clear from this table that, although the gases collected from a radium salt or a radium solution, exhibit marked radioactivity they differ in one important respect from the original radium preparation. When a needle containing a radium salt is tested day after day no change* is detected, but, with the tube containing the gases, the numbers in Table XXIX show that its activity at the end of a month has almost disappeared.

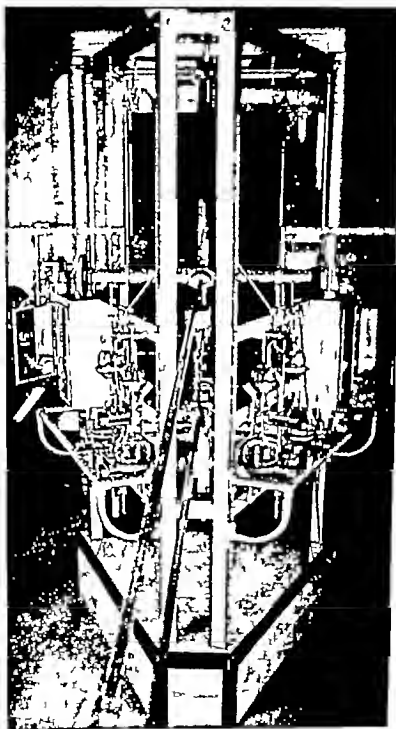
* More accurately at the end of 1 year a loss of 4 parts in 10,000 can be detected.

In addition to the radioactive constituent in the tube the gases collected contain hydrogen oxygen, helium, and carbon dioxide. When these are removed by appropriate means, what is left is a radioactive gas, called *radium emanation* or *radon*. From a gram of radium, only about three fifths of a cubic millimeter at atmospheric pressure can be obtained. Radon has been shown to be an element of atomic weight 222, belonging to the family of the rare gases. Chemically there is nothing remarkable about it, but in radiology it is of tremendous importance. With a suitable emanation plant, it is possible to keep a supply of radium and without touching the original source to seal the radon into glass tubes and use them instead of radium needles. Figures 146 and 147 are photographs of an emanation plant designed by G. Failla of the Memorial Hospital New York, and installed by J. E. Rose in the United States Marine Hospital Baltimore.

TABLE XXIX — DECAY OF ACTIVITY OF RADIIUM EMANATION

Time	Activity	Logarithm of Activity	Change in Log per Day
0	100	2.000	
1 day	83.5	1.922	.078
2	69.7	1.843	.079
3	58.2	1.765	.078
4	48.6	1.687	.078
5	40.6	1.608	.079
6	33.9	1.530	.078
7	28.3	1.452	.078
8	23.6	1.373	.079
9	19.7	1.295	.079
10	16.5	1.218	.077
20	2.7		
30	0.45		

To use a radon tube intelligently it is necessary to be familiar with the law governing its loss of activity that is, of what is called its *decay*. If we plot the results of Table XXIX activity against time, we obtain the curve 1 shown in Fig. 148. Examination of this curve shows it to be exponential, that is, of exactly the same shape as that given in curve 1 Fig. 94. That figure, it will be recalled, illustrates the reduction in intensity of a homogeneous beam of x rays as a result of absorption. As already indicated in section 86 we can describe in three ways an exponential law. In terms of curve 1 in Fig. 148 showing the decay of radon we may state (1) *Each day the activity decreases by 16.5 per cent of the activity of the preceding day*. Thus, if we decrease 83.5 by 16.5 per cent, we obtain 69.7. Or if we decrease 69.7



Courtesy G. Failla and John Quincy

FIG. 146. Semi-automatic control radon extraction apparatus, designed by G. Failla (Memorial Hospital, New York) and installed by J. E. Rose, United States Marine Hospital, Baltimore.

by 16.5 per cent, we obtain 58.2. (2) In 3.83 days the activity has decreased one half. This time is the *half-period* of radon. (3) The curve is exponential, and therefore, is described by the law $I = I_0 e^{-\lambda t}$ where I_0 is the initial activity, t is the time and λ is a coefficient. From this law it follows, as already shown in section 86 that the logarithm of the activity decreases by the same amount each day (or any time interval). This is shown by the numbers in the last column of Table XXIX.

If we use logarithms, the exponential law may be written

$$\lambda = \frac{2.30 (\log_{10} I_0 - \log_{10} I)}{t}$$

For radon this gives us

$$\lambda = \frac{2.30 \times .078}{1} = 0.18,$$

if the time is expressed in days.

It is left as a problem for the student to prove that T , the half-period, that is, the time in which the activity falls by one half (from I_0 to $\frac{1}{2} I_0$, for example) is connected with λ by the relation

$$T = \frac{0.69}{\lambda}$$

For $\lambda = 0.18$, this gives 3.83 days for T .

158. Growth of Radon.—Suppose from a supply of radium chloride kept in solution, all the radon is collected at various time intervals. It is found that, when the solution has been left untouched for a month or two the radioactivity of the collected radon at the end of such an interval is just as great as when the solution is left untouched for six months, or a year or two years, or any long period. On the other hand, if the radon is collected after intervals of 1 day, 2 days, 3 days, and so on the activity is



Courtesy G. Fells and Beth Quinby

FIG. 147. Control panel for radon apparatus shown in Fig. 146. The control room and the radon apparatus are separated by a two-foot concrete wall.

found to be greater the longer the interval, until a maximum is reached after about one month. The numbers in Table XXX and curve 2 in Fig 148, show the exact rate at which the activity increases, maximum activity being assigned the value 100.

The figures of Table XXX are readily interpreted in terms of two processes. (1) The manufacture or growth of radon at a constant rate, and (2) its decay

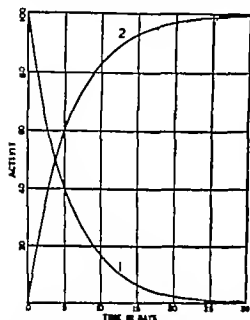


FIG. 148 Graph 1 shows the decay of radium emanation, graph 2 its growth.

in accordance with the law already explained namely that each day the loss of activity of radon is 16.5 per cent of its activity the preceding day. If we start with a quantity of radium salt initially free from radon, each day a certain amount of radon is manufactured, and at first the total amount steadily increases. But, as the total quantity increases, the amount decaying also increases, until ultimately a balance is reached when the loss in a day due to decay is exactly equal to the amount added.

A financial illustration may not be amiss. Suppose a man deposits in a bank \$16.50 every day and, in addition, each day (after the first) before he makes his deposit withdraws 16.5 per cent of the amount to his credit. His account will increase in exactly the same

TABLE XXX—GROWTH OF RADIUM EMANATION FROM RADIUM

Time Interval	Percentage of Maximum Value
1 day	16.5
2	30.3
3	41.8
4	51.4
5	59.4
10	85.5
20	97.3
30	99.5

way as the figures of Table XXX but it will never exceed \$100.00. When that amount is reached, he takes out 16.5 per cent or \$16.50, and puts in exactly the same sum. Equilibrium has been obtained.

159 The Curie and Millicurie. — In much the same way when radon accumulates in a vessel containing a radium salt, a fixed maximum balance or *equilibrium* amount is reached in a little over a month's time. If the quantity of radium is 1 gram, the equilibrium amount of radon is called 1 *curie*; or if 1 milligram of radium is available the equilibrium amount is 1 *millicurie* (mc.) In actual practice, provided the original quantity of radium is sufficient, it is not necessary to wait until equilibrium has been established. From the numbers given in Table XXX it should be evident that from a 100 mg supply of radium, every day a tube containing 16.5 mc. could be obtained. From a 1000 mg source 165 mc of radon are available every day. This can be subdivided among a number of tubes or seeds. For example, sixteen tubes each containing about 10 mc. can be supplied every day by a center possessing 1 gram of radium and an emanation plant.

The use of radon tubes has the great advantage that the original radium supply is left untouched with no danger of the loss which sometimes occurs when radium needles are used. Moreover from a single center tubes with an initial activity of the same order as that of small radium needles can be sent all over the country. On the other hand, in reckoning dosage, radon seeds have the disadvantage that correction must be made for the decay in activity. That, however involves only a little arithmetic.

160 Disintegration and Nature's Transmutation. — If radium emanation disappears, and this seems to be the case, since it steadily loses its radioactivity what becomes of it? As always, experiment helps provide the answer. When a metal wire, preferably negatively charged, is inserted in a tube containing radon, left for two or three hours, and then removed, it is found to be radioactive. Careful investigation shows that the wire is coated with an invisible layer of solid material to which the name *active deposit* is given. If the coated wire is tested by an electroscope at successive time intervals of about 10 minutes, it is observed that the activity steadily decreases.

Now what is the explanation of these changes? The story of the unraveling of these somewhat mysterious radioactive processes, one of the most fascinating in the history of physics, was first given by Rutherford working in collaboration with Soddy about the beginning of this century. To understand it, the student is first asked to recall that an alpha particle has a mass of 4 on the atomic weight scale and a charge of 2 positive units. It is, therefore, an ionized atom of atomic weight 4 and atomic number 2, and these numbers strongly suggest the element helium. Evidence that an alpha particle is indeed a doubly ionized helium atom was found in the early days of the study of radioactivity. Helium was found occluded in radioactive ores, and in 1903

found to be greater the longer the interval, until a maximum is reached after about one month. The numbers in Table XXX and curve 2 in Fig 148, show the exact rate at which the activity increases, maximum activity being assigned the value 100

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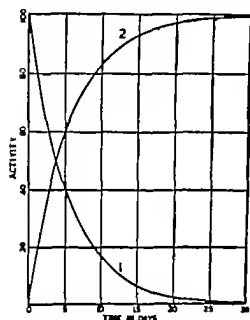


FIG. 148. Graph 1 shows the decay of radium emanation, graph 2 its growth.

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series of successive generations—radium B which changes to radium C by the emission of beta and gamma rays radium C to C by the emission of beta and gamma, and C to D by the emission of alpha (or alternately C to C by the emission of alpha and C to D by emission of beta and gamma) D to E by the emission of beta and gamma E to F by emission of beta and gamma and finally F (polonium) to G by the emission of alpha. There the process stops because radium G is stable being nothing but common lead.

This series of transformations is visualized by the diagrams of Fig 149 and further details about half-periods are given in Table XXXI

TABLE XXXI—RADIUM AND ITS PRODUCTS

Substance	Atomic Weight	Atomic Number	Half-Period	Emission
Radium	226	88	1690 years	alpha
Radon	222	86	3 83 days	alpha
Radium A	18	84	3 0 mins.	alpha
Radium B	214	82	26 8 mins.	beta, gamma
Radium C	214	83	19 7 mins.	beta, gamma
Radium C*	214	84	10 ⁻⁴ sec.	alpha
Radium D	210	82	25 years	beta, gamma
or				
Radium C	214	83	19 7 mins.	alpha
Radium C'	210	81	1 32 mins	beta, gamma
Radium D	210	82	25 years	beta, gamma
Radium E	210	83	5 days	beta, gamma
Radium F	210	84	136 days	alpha
(polonium)				
Radium G	206	82	stable	
(lead)				

* It will be noted that radium C can disintegrate by two different processes to form, after two generations, radium D. Of all the atoms of radium C which disintegrate 99.96 per cent give birth to radium C' and only 0.04 per cent to radium C''

In connection with Table XXXI the following things should be noted.

(1) The half-period of radium, 1690 years, is so long that the total loss, even in the course of a year may be neglected.* For that reason the number of atoms of radon manufactured each day by a given amount of radium is, for all practical purposes, constant.

(2) Because of the long half-period of radium D namely 25 years, it grows very slowly and hence, in a freshly prepared radium salt or tube of radon the amounts of this product and of its posterity are extremely small. The active deposit is a mixture of the products A, B and C

In two months, the actual loss is about 0.007 per cent.

Ramsay and Soddy showed that it was present in radium emanation. But most striking of all was a direct experimental proof made in 1909 by Rutherford and Royds. Alpha rays from a radioactive source enclosed in a vessel were allowed to escape through an extremely thin glass window into a second vessel, where they were collected. By a spectrum test it was shown that helium was present in the second vessel in an amount which gradually increased with the number of alpha particles collected. This proved conclusively that alpha particles were nothing but the nuclei of helium atoms.

We may conclude, then, that the element radium shoots off atoms of helium. In considering where they come from, it is well to recall that the difference between the atomic weight of radium, 226, and that of radon, 222 is 4. The conclusion that the alpha particle is ejected right out of the nucleus of a radium atom can scarcely be avoided. It is an example of the disintegration of an element which occurs spontaneously with radioactive materials, and it is this property which distinguishes a radioactive element from a nonradioactive one.

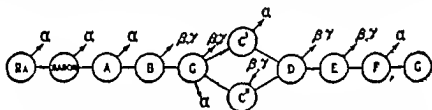


FIG. 149 Schematic representation of transformations from radium to radium G or lead.

The nuclei of the atoms of radioactive elements are unstable, those of ordinary elements stable. (In Chapter XV we shall see that it is possible to *create* unstable isotopes for many elements whose *normal* isotopes are stable.) Due to this instability every now and then an explosion occurs, and a particle is ejected from the nucleus, leaving behind the nucleus of a new atom. This process, therefore is a genuine example of the transmutation of one element into another. Radium, a metal belonging to the barium family is transformed by the ejection of alpha particles, into radon a member of the rare gas group. Since the atomic number of radium is 88 and the alpha particle has an atomic number of 2, the atomic number of radon must be 86.

This transformation or transmutation from radium to radon is but one step in a whole series of successive changes, all of which have been carefully investigated. Atoms of radon are unstable and when they explode, they also shoot off alpha particles leaving behind atoms of radium A. This is another radioactive substance, with a half-period of three minutes. The process of disintegration continues and radium A, emitting alpha particles, is followed by a

series of successive generations—radium B which changes to radium C by the emission of beta and gamma rays radium C to C by the emission of beta and gamma, and C to D by the emission of alpha (or alternately C to C by the emission of alpha and C to D by emission of beta and gamma) D to E by the emission of beta and gamma E to F by emission of beta and gamma and finally F (polonium) to G by the emission of alpha There the process stops because radium G is stable being nothing but common lead

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Radium A	218	84	3.0 mins.	alpha
Radium B	214	82	26.8 mins.	beta, gamma
Radium C	214	83	19.7 mins.	beta, gamma
Radium C*	214	84	10 ⁻⁴ sec.	alpha
Radium D	210	82	25 years	beta, gamma
or				
Radium C	214	83	19.7 mins.	alpha
Radium C**	210	81	1.32 mins.	beta, gamma
Radium D	210	82	25 years	beta, gamma
Radium E	210	83	5 days	beta, gamma
Radium F	210	84	136 days	alpha
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In two months, the actual loss is about 0.007 per cent.

(3) It will be noted that radium itself gives off alpha rays only, although at the beginning of this chapter it has been stated that a radium salt gives off alpha, beta, and gamma rays. There is no real contradiction, however, because if a radium salt is sealed in a tube, disintegration is going on constantly and there is present in the tube a mixture of all the products. From the information given in Table XXXI, it will be seen that gamma rays are emitted by the products B and C. The emission from B is so weak and so feebly penetrating that for all practical purposes, radium C is the source of the gamma rays used in therapy.

We have stated above that, when radon is removed from a radium solution, maximum (gamma ray) activity is not reached for some five hours. This is because it takes that length of time before the maximum amounts of radium B and C are obtained.

(4) The end product, radium G, is stable, being in fact nothing but ordinary lead. In this connection, by means of a little elementary arithmetic, we can make a simple quantitative test. During the successive changes which take place in the transformation from radium to sterile lead, a total of five alpha particles and four beta are emitted. As far as the alpha particles are concerned this represents a reduction in mass of 5×4 or 20 units. Since the mass of a beta particle is so small we can neglect any change in mass due to it, except for very special calculations. Therefore, since the atomic weight of radium is 226 the atomic weight of lead should be $226 - 20$ or 206. Mass spectrograph data show that lead has an isotope of mass 206 in perfect agreement with this calculated value. But long before mass spectrograph data were obtained, Hönigschmid in Vienna in 1914 measured chemically the atomic weight of lead *obtained from pitchblende* and the value he obtained was 206.05*.

By the use of atomic numbers another numerical test may be applied to radioactive transformations. Since an alpha particle has a charge of 2 positive units, a loss of 5 particles means a reduction in the total positive charge of 10 units. A beta particle, however, has a unit negative charge, and hence the loss of 4 beta rays means a decrease in total *negative* charge of 4 units or a *gain* of 4 positive units. The net result, therefore, of the loss of 5 alpha and 4 beta particles is a loss of $10 - 4$ or 6 positive units. Since the atomic number of radium is 88 it follows that the atomic number of lead should be $88 - 6$ or 82 as in fact it is.

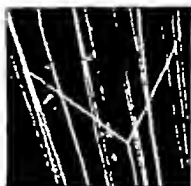
(5) A glance at Table XXXI shows that radium B, radium D, and radium

* The student will recall that the ordinary (chemical) atomic weight for lead is 207.2. This is because it is a mixture of several isotopes.

G or lead have the same atomic number 82. Chemically therefore, these substances have the same properties, since the outer electronic system in an atom of each must be the same. Their atomic weights, however are 214, 210 and 206. They are, therefore radioactive isotopes of one and the same element. As a matter of fact, we owe the name isotopes to Soddy the co-worker of Rutherford in the pioneer work on disintegration because it was this work which first revealed their existence.

161 Artificial Transmutation.—The whole story of disintegration shows that nuclei of radioactive atoms are complex and unstable and strongly suggests the complexity of stable atoms. If this is true, it is possible that a direct hit by a heavy particle like an alpha ray might smash the nucleus of an atom into its constituents. Breaking up the atom in this way must not be confused with releasing some of the electrons surrounding the nucleus. The removal of one or more of these extranuclear electrons does not destroy the atom, for subsequently other electrons are attracted by the ion and the atom returns to its normal state. Breaking up the nucleus is a different matter. It means a complete destruction of the atom and for two reasons it is a very difficult thing to do. In the first place it requires an enormous amount of energy and in the second place, the nucleus must be hit "head-on." In some cases an alpha particle moving at high speed has the necessary amount of energy but the chance of it making a direct hit is extremely slight. As the nucleus occupies about as much space in an atom as a fly in a cathedral, the vast majority of bombarding alpha particles pass right through the atom leaving it intact, except for the occasional removal of an outside electron.

Sometimes the approach to the nucleus is so near that the alpha ray is deflected to one side, and, at the same time, the struck atom—or more accurately its nucleus—has energy communicated to it and moves off to the other side. Figure 150 a cloud track photograph taken when alpha rays were bombarding ordinary helium provides an excellent example of this. It will be noted that the tracks are straight lines for all but one of the particles. As the photograph clearly shows, the single exception is marked by a forked



Courtesy H. Feather and the Royal Society

FIG. 150 Scattering collision of an alpha particle with the nucleus of a helium atom. The alpha ray, travelling along the path marked *x* strikes a helium nucleus and is deflected to travel along one arm of the fork, while the struck nucleus moves off along the other arm.

track, one prong of which corresponds to the deflected path of the original alpha ray the other to the path of the struck helium nucleus.

Occasionally the bombarding particle strikes head-on, and the struck nucleus, if light as hydrogen is shot ahead with high speed. In one of the early experiments, for example, alpha rays bombarded hydrogen, and the protons which had been hit in this way were observed to cause scintillations on a screen placed far beyond the range of the original alpha particle.

And sometimes the alpha particle enters right into or coalesces with the bombarded nucleus, forming a new unstable atom which disintegrates. A transmutation is then the result. In 1919 Rutherford bombarded the gas



Courtesy P. M. S. Blackall and the Royal Society

Fig. 151 Disintegration collision of an alpha particle with a nitrogen atom. The alpha particle, travelling along the path marked Λ , collides with a nitrogen nucleus and is captured. A disintegration results, the left-hand, long, thin arm of the fork marking the path of an ejected proton, the right-hand short, fat arm, the path of an ejected oxygen atom.

nitrogen with alpha rays and obtained hydrogen because of such a process. This is then an example of what we shall call artificial transmutation to distinguish it from the spontaneous natural transmutation of radioactive materials. The amount of hydrogen manufactured was too small to be detected by chemical means, but the most rigid tests showed that the effect was none the less real. There was no doubt about it. Protons or hydrogen nuclei were knocked out of nitrogen nuclei. The process of obtaining hydrogen in this way was not very economical, for a million alpha particles had to be fired to give one direct hit, and so to form one atom of hydrogen. But it was not the quantity of hydrogen evolved that mattered, rather the fact that a direct proof had been given that protons existed in the nuclei of nitrogen atoms. Within a few years it was shown that protons could be knocked out of many other atoms as well and the view that all nuclei are composed of electrons and protons became widely held. In the light of subsequent work, some of which will be given in Chapter XV this view had to be altered.

Later we shall show that when an alpha particle interacts with a nitrogen nucleus with the emission of a proton an oxygen atom is also formed. A cloud track photograph of this transformation taken a number of years after Rutherford's classic experiment, is shown in Fig 151. In this photograph note the fork at the end of one of the alpha ray tracks. The long, thin "streak" forming one arm of the fork, corresponds to the proton path the much shorter and somewhat irregular second arm to the track of the oxygen atom.

162 Protection. — As with x rays, so with radium it is highly important to protect from possible serious injury all who work with radium in any capacity. If a radium preparation is carelessly handled beta rays may injure the hands to such an extent that cancer ultimately develops. "Ten milligrams of radium, or ten millicuries of radon in a small tube thin enough to permit the escape of most of the beta rays, at a distance of 3 mm from the skin, will deliver enough radiation to produce a sharp reaction in 10 minutes exposure (Qumby). For that reason to quote from the 1937 International Recommendations, "the radium should be manipulated with long handled forceps, and should be carried from place to place in long handled boxes, lined on all sides with at least one centimeter of lead."

Gamma rays may also have important injurious general effects, and an adequate thickness of a protective material like lead should be used. Moreover care should be exercised that a worker is shielded not only from the direct beam, but from scattered rays as well.

In an appendix the recommendations for x ray and radium protection are given.

163 Other Radioactive Families. — In Table XXXI we have listed the various members of the radium family. These however are by no means the only radioactive substances which occur in Nature. Radium itself is a descendant through several generations of uranium I a radioactive element of atomic number 92, atomic weight 238 with a half-period somewhat less than 5×10^8 years.

Two other important families consist of actinium and thorium products. One of the members of the latter family is mesothorium a substance which with an atomic number of 88 is an isotope of radium. For that reason, if radium and mesothorium are present in the ore from which radium is extracted it is not possible to separate them by ordinary chemical means, and sometimes radium salts contain mesothorium as an impurity. This is not desirable, because although mesothorium emits gamma rays, its activity decreases about 10 per cent in a year, unlike radium which, as we have seen, remains sensibly constant.

track, one prong of which corresponds to the deflected path of the original alpha ray, the other to the path of the struck helium nucleus.

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Courtesy P. M. S. Blackett and the Royal Society

FIG. 151. Disintegration collision of an alpha particle with a nitrogen atom. The alpha particle, travelling along the path marked α , collides with a nitrogen nucleus and is captured. A disintegration results, the left-hand, long, thin arm of the fork marking the path of an ejected proton, the right-hand short, fat arm, the path of an ejected oxygen atom.

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gamma rays, can be obtained from a single tube, with intensity comparable with that of a radium source of 1000 grams.

(4) By means of supervoltages extremely high speed cathode and positive rays can be obtained. With such particles bombardment experiments can be carried out with results of great importance in the field of radiology. For example we shall see in the next chapter that by such means artificial radioactive materials can be manufactured.

The fact that million volt x ray outfits are in operation in such centers as the Memorial Hospital New York, the Huntington Memorial, Boston and St. Bartholomew's Hospital London is ample evidence of the importance of supervoltage in radiology.

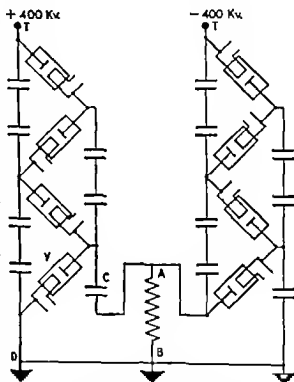
A number of different methods have been used for the development of supervoltages. Some of them are simple in principle some are engineering jobs on a large scale. In the following sections we shall examine briefly the main features of the more important methods.

165 The Induction Coil.

—Some years ago the General Electric constructed a special induction coil which could be run continuously at 700 000 volts. This was used for two or three years at the Memorial Hospital, but interrupter troubles create difficulties in connection with induction coils, and it is not likely that much use will ever be made of them for supervoltage work.

166 The Cascade Generator —

In this type, as developed by the Philips Laboratories and the General Electric Corporation use is made of a combination of condenser and rectifying valve units similar to those used in the Villard and Greinacher rectifying circuits. (Sections 76 and 77) An arrangement utilized in a Philips generator of this sort, capable of developing 800 000 volts, is shown in the diagram of Fig. 152. In this figure it will



Courtesy Philips Laboratories

FIG. 152. The arrangement of rectifying valves and condensers in a cascade generator

CHAPTER XIV

PRODUCTION OF HIGH VOLTAGE. PART II

SUPERVOLTAGE TUBES AND HIGH SPEED PARTICLES

164 Importance of Supervoltage. — During the last decade the construction of supervoltage machines has played an important part in the development of radiology physics. In Chapter II only a passing reference was made to this work, because it was considered advisable to defer the discussion until the reasons for using supervoltages could be made clear. Let us now examine some of them

(1) From the relation

$$\text{Shortest wave length} = \frac{12,354}{\text{maximum voltage}},$$

we see at once that the higher the voltage across a tube, the shorter the minimum wave length in the continuous x ray spectrum. With a million volts, for example the shortest wave length is about 0.012 angstrom. The wave length of maximum intensity in the continuous spectrum is, of course, some what longer than this.

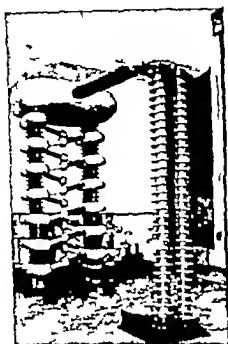
Obviously then by using supervoltages, extremely penetrating beams of rays can be obtained. Now there is some evidence, although it is by no means conclusive, that extremely short wave lengths are preferable to longer ones for biological reasons. In any case it is desirable to examine carefully the effects of as wide a range of wave lengths as can be obtained.

Moreover the more penetrating the x ray beam the greater the percentage depth dose, that is, the greater the percentage of the surface dose delivered to deep-seated tissue. (See again section 146)

(2) The intensity of a beam of x rays increases steadily with increasing tube voltage, hence ultrahigh intensities may be obtained with supervoltage machines.

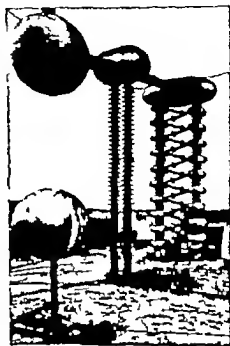
(3) With sufficiently high voltages (about two million), wave lengths comparable with those of gamma rays from radium C may be obtained. Since the world supply of radium is limited, an artificial substitute would be a great boon. Already it has been demonstrated that x rays, the equivalent of nature's

In all supervoltage generators ample room must be left between the high tension terminals and the ceiling or other grounded places, otherwise "flash overs" will take place.



Courtesy Philips GlasOscop/Fabrikat

FIG. 154. A 12,500,000 volt cascade generator



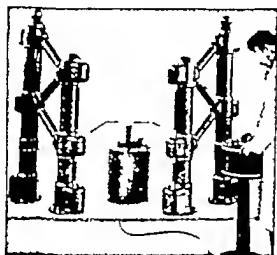
Courtesy Philips GlasOscop/Fabrikat

FIG. 155. The negative end of a 4,000,000 volt cascade generator

167 Van de Graaff Electrostatic Generator — A generator much simpler in principle than the cascade type and much cheaper to construct has been developed during the last decade. The first machine of this type was the invention of Van de Graaff who made use of fundamental ideas discussed in elementary classes in electrostatics.

The student is asked to recall two of these. (1) An electric charge given to a hollow conductor goes to the outer surface, the potential at all points within such a conductor being the same. (2) An insulated charged conductor loses its charge if a pointed conductor is in contact with it or conversely an uncharged insulated conductor with a sharp point attached to it, will pick off a charge from a charged body placed near the point. In the first case, we sometimes state that the charge slips off the point. Actually the charge accumulates on the point to such an extent that the resulting electric field in the air near the point is great enough to ionize the air. If the point is nega-

be noted that the circuit BAC_1V_1D is similar to the Villard circuit of Fig 87, except that only one rectifying valve and one condenser is used. By adding successive condenser valve units in the manner shown in the figure, the original E.M.F. developed in the secondary AB of the high tension transformer may be so multiplied that terminal T is raised to a high positive potential, T_1 to an equally high negative. In the generator represented in this figure, with a transformer voltage of only 100,000 volts T becomes +400,000 volts, T_1 - 400,000 volts, hence between the terminals there is a P.D. of 800 000 volts. The photograph reproduced in Fig 153 shows the actual appearance of this generator or one similar to it, whose total height is some 8 feet.



Courtesy Philips Gloeilampenfabrieken

FIG. 153. Photograph of a cascade generator

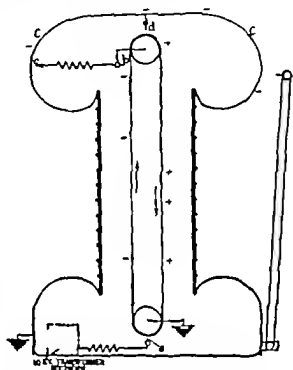
Making use of the same principle, the Philips Company constructed a much larger generator for the Cavendish Laboratory Cambridge England. This machine, which has a total height of about 17 feet, develops 1,250 000 volts, although only 120 000 volts is necessary in the secondary of the transformer. Figure 154 shows the actual appearance of this generator. In this figure the generator proper with its zig zagging valves is seen on the left. The double column on the right contains an extremely high resistance which is used in the measurement of the actual voltage developed by the method described in sections 27 and 168. The horizontal piece at the top of the photograph is a damping resistance by means of which electrical connection is made to the top of the measuring resistance (as shown) and to the x ray tube (not shown).

Figure 155 is a photograph of the negative end of a 4 000 000 volt generator used in the Philips Laboratory at Eindhoven Holland. An added feature in this photograph is the huge sphere gap used for taking voltage measurements (see section 23)

The important details of the construction of a 500 000 volt generator may be understood by reference to Fig. 157. An electric charge is accumulated on a hollow insulated conductor *C* some thirty inches in diameter and twelve inches high which stands on the top of an insulating column over three feet long and twelve inches in diameter. The column rests on a supporting base in contact with ground.

Within the base there is a small transformer rectifier unit so arranged that a negative charge slips off a row of points, one of which is represented by *a* in the diagram. These points are about one quarter inch from a grounded pulley revolved by a motor also housed within the base. A three-ply rubber fabric, making an endless belt about ten inches wide, passes around this pulley and a second insulated pulley placed inside the insulated conductor at the top of the generator. When the machine is in operation the motor keeps the belt moving at the rate of 5000 ft. per minute. A collector rod with points at *b* and at *c* is attached to the upper insulated pulley.

The action of the generator is somewhat as follows. As the left hand side of the belt goes up with its negative charge negative electricity is picked off at *b*. Most of this slips off at *c* going to the outside of the terminal, but some goes to the insulated pulley. Since this is situated inside a hollow conductor normally its potential would be the same as that of the conductor but when a free charge of the same kind is thus added to it, its (negative) potential becomes higher than that of the terminal conductor. Hence, when a row of pointed conductors is attached to the inside of the terminal as represented at *d*, the higher negative potential of the pulley causes an escape of positive electricity from these points. This escape of positive (1) still further increases the negative charge on the terminal (2) annuls any negative left on the upward belt and (3) puts a positive charge on the downward belt. At the bottom



Adapted from Generation by J. O. Thompson, F. H. Merrill and F. J. Seaford

FIG. 157 Outline diagram of small Van de Graaff generator

tively charged positive ions move towards it and annul its charge, thus leaving negative ions in the surrounding region. Similarly, before a point picks off a charge, there is ionization between it and the neighboring charged body.

To understand the way in which these ideas are utilized in the Van de

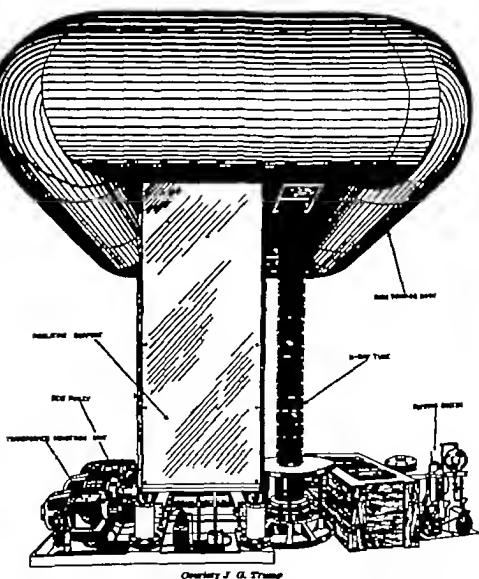


FIG. 156. A Van de Graaff generator capable of developing 1,000,000 volts or more.

Graaff generator a brief description is given of a comparatively small machine, designed by J. G. Trump and R. J. Van de Graaff of the Massachusetts Institute of Technology. The general appearance of one generator of this kind, capable of developing a million volts or more, is shown in Fig. 156.

appearance of such a measuring resistance. This particular resistance, or one very similar to it, is made of 2000 oil immersed carbon units, each of 0.75 megohm that is, with a total resistance of 1500 million ohms. A high voltage of about a million and a half volts, then causes a current of about 1 ma. through this resistance. By means of an electrostatic voltmeter with a range up to 1500 volts, the potential difference across 1/1000 of the resistance is read directly off this instrument placed on the control panel of the machine.

(4) *Generating Voltmeter* — An entirely different method which is being successfully used for supervoltages, makes use of a simple fundamental idea. The student will recall that, when an *uncharged* insulated conductor such as *BC* Fig. 158 is placed in the electric field near a *charged* conductor *A* induced charges appear at the opposite ends of the uncharged conductor. If



FIG. 158 Induced charges of opposite sign appear at the ends of an uncharged conductor placed in the field of a charged conductor

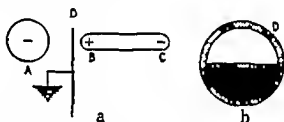


FIG. 159 A to-and-fro movement of charges takes place in the conductor *BC* when the disc *D* is rotated.

A has a negative charge, the induced charge at the near end *B* is positive, at the far end, negative. (If the conductor *BC* is grounded, the end *B* will still be positive, and negative will go to earth.)

Now suppose that a grounded metallic disc *D* cut as shown in Fig. 159*b* so that nearly one half is removed, is placed between the conductors *A* and *BC* as shown in Fig. 159*a* and rapidly revolved. It should be evident that, when the open part of the disc is opposite the end *B* the conductor *BC* is under the influence of the charge on *A* and so induced charges appear as before. But, when the uncut half of the grounded disc is in front of *B* *BC* is shielded from the field of *A* and hence during that interval this conductor returns to its normal state. Since the disc is in rapid revolution, it follows that there will be a surging to and fro of electric charges, that is, an alternating current whose frequency is controlled by the speed of the disc. Moreover the greater the potential of *A* the greater the intensity of the electric field causing the movement of the charges, and the greater the magnitude of this alternating current. Hence, if we can measure the strength of this current, we are provided with a means of measuring also the potential of *A*.

of its downward path the positive is annulled by the spraying action of the discharge points at *a*, and the process goes on until, in this particular instrument, the terminal attains a potential of 500,000 volts.

The value of the maximum attainable potential depends on the insulation and the shape of the upper terminal. In this connection it is worth while noting that an upper limit to the potential which any charged body may attain is reached when the electric field near any part of its surface has the value of about 25 to 30 Kv per cm. When fields of this intensity are reached, ionization and corona discharge sets in. The smoothly rounded top of the generator is, of course, designed so that the highest voltage possible is attained before such a field strength is reached.

By the use of compressed air or the gas freon much higher voltages may be developed before any break down discharges occur, and more than one generator of the Van de Graaff type has made use of this fact. A million volt machine has been in operation at the Huntington Memorial Hospital, Boston for two or three years. More recently a generator has been built by Trump and Van de Graaff capable of developing 1250 Kv. This is housed in a steel tank 100 in. high 34 in. in diameter, containing air at a pressure of 11 atmospheres.

168. Measurement of Supervoltages. — In sections 23 to 28 Chapter III some discussion was given of methods used in the measurement of high tension voltages. When potentials of the order of a million or more are used, naturally there are added difficulties, although the principles employed in most of the methods do not differ greatly from those already given.

(1) If the supervoltage is used to operate an x ray tube, the maximum voltage applied to the tube can always be calculated from a measurement of the shortest wave length in the continuous spectrum. Reference has already been made to this method in sections 28 and 103.

(2) Values of supervoltages may be estimated with spark gap meters, although calibration values are somewhat uncertain. The large size of spheres used as large or larger than 100 cm. in diameter may be seen by a glance at Fig 155. It is interesting to note that, in the High Voltage Engineering Laboratory at Pittsfield Mass. spheres of spun aluminum, over 6 ft. in diameter permit direct measurements to be made up to three million volts.

(3) In section 27 reference was made to a method in which a high potential difference may be evaluated by placing an extremely high resistance in parallel with the unknown high voltage terminals, and then measuring the potential drop across a known fraction of the whole resistance. Attention has already been directed to Fig 154 which shows on the right-hand side the external

insulation must be so good that there is no danger of spark-over on the outside of the tube itself. Care must be exercised to guard against a discharge in the tube even with a cold filament, because once an electric field reaches a certain value electrons can be pulled out of a cold metal. A good vacuum must be maintained in a tube, frequently of such large dimensions that vacuum pumps have to be in continuous use. Then, too, there are the added precautions necessary to protect both operator and patient from the dangers of electrical shock and from powerful beams of very penetrating rays.

The different ways in which these and other difficulties have been overcome will be understood from the following brief description of a few representative supervoltage tubes.

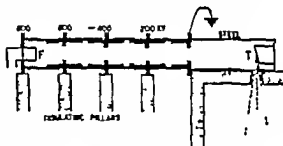
The General Electric Company has constructed, along more or less standard lines, a sealed-off tube some five feet long which is capable of operation on 400 000 volts. In this tube by placing the target near the inner end of a long hollow copper cylinder electrons are prevented from bouncing off the target and charging the inner surface of the walls of the tube, one of the common causes of tube puncture. The envelope itself one quarter of an inch thick, is made of borosilicate glass, a material with high dielectric strength.

For much higher voltages, this firm has constructed multisection tubes, that is, tubes consisting of a number of glass cylinders separated

by metal rings. Since the metal used is an alloy with the same coefficient of expansion as the glass, vacuum tight seals can be made. The metal rings are attached to electrodes extending inside the tube. By the use of these intermediate electrodes the total voltage between the filament and the target is subdivided and "the metal cylinders exert a focusing action on the electron beam and protect the glass from bombardment" (Read)

Figure 161 adapted from an illustration in an article by J. Read in the *British Journal of Radiology* represents a large 800 000 volt tube of the multisection type built by the General Electric Company for the Swedish Hospital, Seattle. It will be noticed that the voltage across each section is only 200 000 and that the target is at ground potential. The whole tube lies outside the treatment room which is heavily insulated against penetrating rays except for the window through which they pass to the patient.

Another General Electric tube of the multisection type consists of ten



Adapted from illustration in the *British Journal of Radiology*

Fig. 161 An 800,000 volt x-ray tube of the multisection type.

In *generating voltmeters* this principle has been utilized as a satisfactory means of measuring supervoltages. As an example of the way in which the principle is applied, a brief description is given of the essential features of an instrument of this kind recently described by Trump, Safford, and Van de Graaff, and used by them for the measurement of voltages, as high as a million and a half, generated by their high pressure electrostatic generator. Suppose the end *C* of the conductor *BC* is joined as illustrated in Fig 160

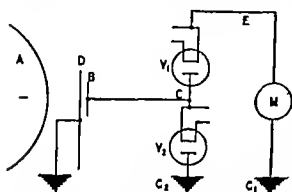


FIG. 160 When the disc *D* is rapidly revolved an intermittent but unidirectional current flows through the microammeter *M*

a current measuring instrument such as a microammeter. Through this instrument, therefore, there is an intermittent, but unidirectional current which, if the disc *D* revolves quickly enough is recorded as having an average mean value.

The arrangement actually used is not quite so simple as that shown in Fig 160. Since theory shows that the current through the microammeter is proportional to the frequency of the rotating disc, this is made with four sectors, equal in area and equally spaced (not unlike a Maltese cross) and the end *B* directly behind the disc, consists of eight brass sectors mounted on a Textolite ring. Alternate sectors (of *B*) are electrically joined to form two sets of four each and each set is joined to a separate double diode tube. In this way one set of four is shielded when the other set is not, and by a simple extension of the means illustrated in Fig 160 "substantially constant rectified current flows in the microammeter circuit".

In the actual instrument, the connection similar to *E* of Fig 160 is a long shielded conductor and the microammeter is mounted on a panel fifty feet from the electrostatic generator. The scale is calibrated, and supervoltage read directly from the instrument.

169 Supervoltage Tubes.—The problem of building tubes capable of operation at voltages of a million or more presents many difficulties. The

to a point between the plate and the filament of two rectifying valves. (Actually a double diode valve is all that is necessary) Then when *B* is not shielded and *A* is negative, electrons flow from the end *B* through the valve *V*₂ to ground at *G*₂, leaving the end *B* positive. When *B* is shielded, electrons cannot cross valve *V*₂ to annul the positive charge, but they can cross valve *V*₁ flowing from ground at *G*₁ through *M*,

Therapy Department, at St. Bartholomew's Hospital, London. This tube thirty feet long and weighing ten tons, extends horizontally through three rooms. In the first room a generator can maintain the cathode at a negative potential of 500 000 volts or more. The central part of the tube a grounded steel cylinder containing the water-cooled gold target, lies in the middle or treatment room. Since in the third room a second generator can maintain the anode at a positive potential of 500 000 volts, potentials of at least 1 000 000 can be applied to the tube. The anode and cathode ends are separated from the middle portion by porcelain insulators, each five feet long and elaborate precautions are taken to provide adequate protection from the rays. In this connection we quote from a booklet describing this installation. The portion within the treatment room that is, the central twelve feet, is surrounded by a protective sheath, consisting of a six inch layer of close-packed lead shot, enclosed between two coaxial steel cylinders. An aperture in this sheath allows the transmission of the x ray beam. The protective sheath in its turn is surrounded by a steel cylinder which carries the filters, diaphragms, and applicators for defining the x ray beam. The protective sheath and applicator cylinder can be rotated independently of each other. In this way it is possible to direct the beam of x rays at will either through the applicator towards the patient, or into an absorbing lead saddle six inches thick, suspended immediately above the tube. Thus, the portion of the x ray tube within the treatment room is both shock-proof and ray-proof."



Courtesy J. G. Thompson

FIG 163 The lower end of the million volt x-ray tube shown in Fig. 162.

170 High Speed Particles. The Cyclotron. — In section 161 it was shown that by bombarding nitrogen with alpha particles, both hydrogen and oxygen can be manufactured. The process is not very efficient because

sections, is 28 ft 6 in long, and is able to carry 10 ma. at 1,400 000 volts.

In most of the supervoltage tubes, the necessary low pressure has to be maintained by the continuous operation of exhaust pumps. The Philips Company, however have utilized successfully the multisection principle in the construction of sealed-off tubes capable of withstanding supervoltages. In the Philips tubes, each unit has glass ends of the re-entrant type, somewhat as used in the ordinary metal tube, Fig 58, and the units are connected by soldering external metal pieces at adjacent ends after each unit has been separately evacuated.

Connection between the units is subsequently made by the electron beam itself, which perforates thin pieces of metal foil covering the central parts of the metal electrodes. A two-unit tube of this type has been constructed capable of operation on 700 000 volts and a three-unit tube, 6½ feet long, is capable of continuous operation with 1 or 2 ma., at 1 000 000 volts.



Courtesy J. G. Trump

FIG. 162. The million volt x-ray tube in the Huntington Memorial Hospital of the Harvard Medical School.

A million volt tube of an entirely different construction developed at the Massachusetts Institute of Technology in connection with an electrostatic generator is in use at the Huntington Memorial Hospital of the Harvard Medical School. The general appearance of this tube is shown in Fig 162 (See also Fig 156) Insulation is provided by using a ten foot column of twenty porcelain sections resting on a grounded steel flange at floor level. Below the flange a steel cylinder which forms the lower end of the x ray tube continues into the treatment room as shown in Fig 163. Electrons from a filament at the top of the tube are guided down the tube by electrostatic lenses, placed between each porcelain sector until they strike the water-cooled

lead target sixteen feet below. "The target consists of a copper cup on the inside of which a 15 mil lead coating has been electroplated, the cup being cooled by a water jacket. The target is at ground potential but insulated from the tube extension so that the current to the target can be read on a milliammeter at the control panel. The x rays utilized in treatment are those transmitted downward through the target and water-cooling jacket." (Trump and Van de Graaff)

By way of contrast to this tube, a brief reference is made to one made by Metropolitan Vickers for use in the Mozelle Samson High Voltage X Ray

34 and 35) positive rays (section 43) and alpha particles (section 150) Let us examine this deflection a little more carefully

According to the motor principle when a wire such as *AB* Fig 165 carries a current and lies in a direction at right angles to a magnetic field

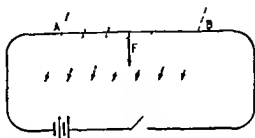


FIG. 165 The wire *AB* when carrying a current and lying in a direction at right angles to a magnetic field is acted on by the force at right angles to the wire and to the field.

(represented by the lines with arrows) it is acted on by a mechanical force in a direction perpendicular to both the wire and the magnetic lines. In Fig 165 if the current, that is, the direction of positive flow is from *A* to *B* the force on the wire is in the direction represented by *F*

Now a current is nothing but a flow of charges, hence a stream of any kind of electrified particles, whether cathode rays or positive ions, constitutes a current. If, as in Fig 166 *CD* represents the path of a stream of positive ions, there is a current in the direction *CD*. If therefore, a magnetic field exists with lines running at right angles to the direction of motion of the ions, a mechanical force must act on the ions. Since this force is always perpendicular to both the field and the current, it is not difficult to see that the ion path must be curved as in Fig. 166. If the field is uniform and the speed of the ions constant, the curve is the arc of a circle.

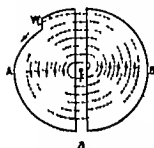


FIG. 166. Particles carrying a positive charge when travelling in a direction *CD* at right angles to a magnetic field are subjected to forces *F* which make the particles move in the arc of a circle.

Again for ions moving at constant speed, the magnitude of the mechanical force is directly proportional to the strength of the magnetic field. It follows that the stronger the field, the more curved the path of the ion. On the

a direct hit between the nucleus of a nitrogen atom and the bombarding alpha particle must take place, and the chances of this are only about one in a million. The results of this and similar bombarding experiments are so important, however, both in physics and in radiology, that ways and means have been sought of supplementing the limited supply of alpha particles by other high speed projectiles. This can be done in two important ways.

(1) By speeding up positive ions with supervoltages. As we have already emphasized, the greater the potential difference through which a charged particle falls, the greater the kinetic energy which it acquires.



Adapted from *Physical Science Construction*

Fig. 164. A and B represent the D's or dees of a cyclotron. An ion originating at F spirals around and around until it emerges through a thin window W with very high speed.

The high voltage generators we have been describing therefore, are sometimes used to accelerate ions along suitably constructed tubes. At the end of their journey these ions may be used to bombard materials.

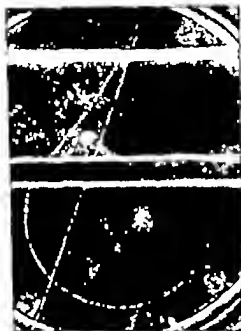
(2) By the use of a *cyclotron*. Since this is the method

which has been developed with great success and since its use has led to results of great importance in radiology its basic principles will be described somewhat in detail.

Fundamentally the method employed in the cyclotron consists in giving an ion at regular intervals a succession of low voltage pushes until it acquires the speed equivalent to a high voltage. The ion, after moving at a low speed through a half-circle of small radius receives a push which sends it on at greater speed in a half-circle of larger radius at the end of the second half-circle, receiving another push it goes off moving still more quickly in a still greater half-circle. The process continues, half-circles being executed at greater and greater speeds and with greater and greater radii until after a few hundred or more revolutions, the ion is moving so quickly that its energy is the same as if it has fallen through a potential difference of a few million volts. In Fig 164a, the curved dotted line represents a few turns of the spiral path of such an ion.

For the satisfactory operation of such a scheme two things are necessary (1) The ions must be made to move in circular paths; and (2) the pushes must be properly timed. The first condition is easily realized by an application of the motor principle to which a somewhat general reference was made in connection with the deflection by a magnetic field, of cathode rays (sections

To make sure that the ions whirl around after the manner depicted in Fig. 164 the arrangement must be such that after the completion of each half-circle, an ion receives a push making it go a little faster in the next half circle. The solution of this problem is simplified because the time taken by an ion to cover a half-circle is the same regardless of its radius. It is easy to see the reason for this. It simply means that the greater speed of the particle in a circle of greater radius just compensates for the longer path.*



Courtesy Carl Anderson, Beta H. Yodanis, and the Physical Review

FIG. 168. The straight track is due to a very fast cosmic ray the circular path in the lower half to comparatively slow positron which originated in the lead plate. The exact circular path illustrates the effect of uniform magnetic field on moving electrified particle.



Courtesy Beta H. Yodanis

FIG. 169. The opposite curvatures of the tracks originating in a center C show the existence of both positive and negative particles.

To give an ion a push at the end of each half-circle, use is made of the rapidly alternating voltages which can be maintained between two conductors by means of high frequency circuits. In Chapter XVI certain details about such circuits will be given but, as they are nowadays in common use, being of

* The time to execute a complete circle $= \frac{2\pi r}{v}$. From the data given in the foot

note on page 210 this may be written $\frac{2\pi m}{He}$ an expression whose value does not depend on the radius.

other hand, if the magnetic field is kept constant, slowly moving ions are deflected more readily than fast ones.* The curved paths of electrified particles are beautifully illustrated by cloud track expansion chamber photographs. Suppose that *HKLM* Fig 167*a* represents a cross-section of a cloud track chamber placed in the strong uniform magnetic field represented by the dotted lines. If a photograph is taken when an ionizing particle is moving along *CD* the trail of ions will be curved, somewhat as shown in the top view, Fig 167*b*. Actual photographs showing this are reproduced in Fig 168 and Fig 169. In Fig 169 note (1) the closed circles which indicate the presence of very slowly moving particles (2) the much less curved tracks, which indicate faster ions. The two opposite curvatures of the trails of the faster ions provide evidence of both positive and negative particles. (See section 180)

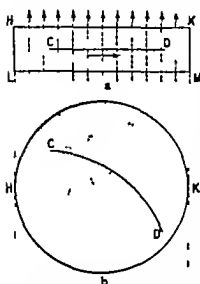


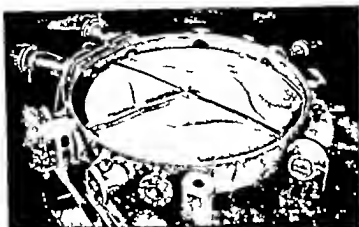
FIG. 167 By using a cloud chamber the curved path of a charged particle in a magnetic field may be revealed.

The circular trail in the lower half of Fig 168 shows clearly how, by the application of a suitable magnetic field, it is possible to make electrified particles move in circles. To deflect particles of atomic size strong magnetic fields are necessary and the construction of a sufficiently powerful electromagnet for a good cyclotron is a big job in itself. Here are a few details about the magnet used in the cyclotron illustrated in Fig 170, one of the earlier instruments built under the direction of E. O. Lawrence of the University of California. The pole faces are over two feet in diameter

The total weight of the magnetic circuit consisting of seven sections of cast steel is about 65 tons." The copper coils carrying the current which magnetizes the iron weigh about nine tons and are immersed in oil. The large drum like pieces shown in the photograph represent the outer casing surrounding these coils.

* A particle with charge e and velocity v is equivalent to a current ev . Application of the motor principle shows that the mechanical force deflecting the particle is Hev where H is the intensity of the magnetic field. Since, when a particle of mass m moves with constant velocity v in a circle of radius r the centripetal force is $\frac{mv^2}{r}$, we may write $\frac{mv^2}{r} = Hev$, or $r = \frac{mv}{He}$. Hence the smaller v , the smaller r or the more curved the path.

pushed from *A* to *B* on the right side of the box, in the next half-cycle it will be pushed from *B* to *A* on the left, and so continue on its circular motion in paths which ever widen because of the increase in speed each half revolution



Courtesy W. J. Henderson

FIG. 171 The dees in the Purdue University cyclotron.

Just before the sides of the box are reached, the ions pass through a window into an observation chamber

Sometimes the ions emerge through a thin metal window into the surrounding air. When this is the case they strike the molecules of the air and cause



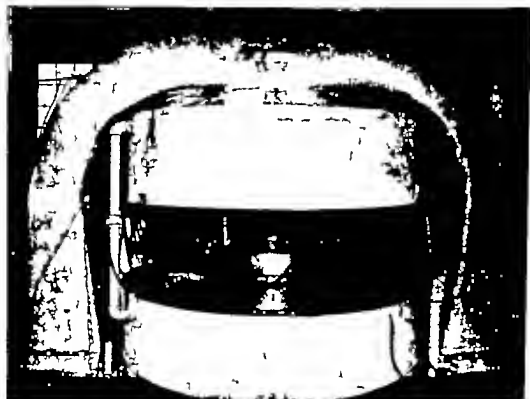
Courtesy W. J. Henderson

FIG. 172. Another view of the dees in the Purdue University cyclotron.

them to emit light of a lavender color. The path of the ionic beam is then marked by a column of light extending for some distance from the window. This is beautifully shown in Fig. 173 a photograph taken by Professor Lawrence using deuterons (nuclei of heavy hydrogen) possessing some five or six million electron-volts of energy.

If a single push is given by a potential difference between the dees of

the type necessary for the generation of radio waves, most readers will realize that it is not a difficult matter to maintain between the two conductors marked *A* and *B* in Fig. 164 a potential difference of several thousand volts which alternates from *A* positive and *B* negative to the reverse, a few million times a second. In the actual instrument *A* and *B* are hollow semicircular boxes frequently called D's or dees, somewhat as shown in Fig. 164*b*, which lie in the



Courtesy E. O. Lawrence

FIG. 170. A view of one of the cyclotrons constructed under the direction of E. O. Lawrence.

region between the pole pieces of the powerful magnet. In Fig. 170, the position of the dees is clearly shown right at the center of the photograph. Figures 171 and 172 reproduced through the kindness of W. J. Henderson are photographs of the dees used in the cyclotron recently constructed in the Physics Department of Purdue University.

When the machine is in use the air is exhausted from the boxes, a little gas such as hydrogen is allowed in at low pressure and ions are created at the center by some such device as a heated filament. The value of the magnetic field and the frequency of the oscillating electric circuit are so chosen that during the time of a reversal of voltage between *A* and *B* the ion to be speeded up moves through exactly half a circle. Whenever therefore, an ion is

CHAPTER XV

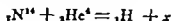
ARTIFICIAL RADIOACTIVITY

171 Nuclear Bombardment.—The results obtained by bombarding substances with high speed particles have justified many times over the time and energy expended in the development of supervoltage machines. In this chapter reference is made to some of the important discoveries made in this way with special emphasis on those relating to radiology. At the outset the student should become familiar with the following method of describing in symbols a nuclear interaction.

In section 36 it was pointed out that to describe an atom without ambiguity both its atomic weight and its atomic number must be given. Analysis by the mass spectrograph has shown in addition that on the atomic weight scale masses of all atoms are given by numbers which depart from integers by very small amounts. With these facts in mind it is easy to see why an isotope of an element is frequently designated by the symbol ${}_a^bX$ where X is the customary chemical symbol, a is the atomic number and b the mass number that is, the integer which with slight error represents the atomic weight. Thus, H^1 represents ordinary hydrogen, ${}_1H$ or D^2 heavy hydrogen or deuterium, He^4 helium or an alpha particle and ${}_{80}^{200}Hg$, ${}_{80}^{201}Hg$, ${}_{80}^{202}Hg$, ${}_{80}^{203}Hg$, ${}_{80}^{204}Hg$ various isotopes of mercury.

Whenever the nucleus of an atom moving at high speed strikes the nucleus of another atom and an interaction takes place, whatever the final products, the total nuclear charge and, at least to a first approximation* the total mass must remain constant. If, then we write down an equation describing the nuclear reaction the sum of the charges and of the masses on one side must equal the corresponding sums on the other side.

As an illustration consider again the pioneer experiment of Rutherford when he obtained protons (${}_1H$) by bombarding nitrogen (${}_7N^2$) with alpha particles (${}_2He^4$). In symbols we can write



* This assumes the validity of the law of conservation of mass. Actually in nuclear reactions, the total mass before may differ very slightly from the total mass after the reaction. This question is discussed and explained in section 184.

10,000 volts and an ion makes 200 revolutions, it has received 400 pushes or the equivalent of $10,000 \times 400$ or 4,000 000 volts. Actually protons and deuterons and nuclei of helium atoms with much greater energy values than this have been obtained. Values as high as 20,000,000 electron volt



Courtesy E. O. Lawrence

FIG 173. A close up photograph showing the luminescence in air caused by a beam of high energy deuterons emerging from a cyclotron

deuterons have been reported. Cyclotrons have been constructed at various large centers, and valuable results obtained by bombarding substances with the high speed particles so obtained. In the next chapter we shall discuss in detail those results which have proved of value to radiologists.

CHAPTER XV

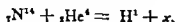
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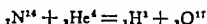
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As an illustration consider again the pioneer experiment of Rutherford when he obtained protons (H) by bombarding nitrogen (${}_7N^{14}$) with alpha particles (${}_2He$). In symbols we can write



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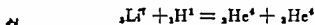
where x is a product which must have the mass number 17 since $14 + 4 = 1 + 17$; and the atomic number 8, since $7 + 2 = 1 + 8$. Since 8 is the atomic number or the distinguishing mark of oxygen, x must represent an isotope of this element of mass number 17, or we may now write



As we have already pointed out, long after Rutherford performed this experiment, analysis by the mass spectrograph showed that oxygen has an isotope of mass number 17

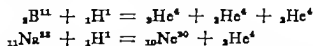
A still more abridged notation, making use of the symbol α for alpha particle, p for proton, writes the above reaction $\text{N}^{14}(\alpha, p)\text{O}^{17}$ which means that nitrogen of mass number 14 when bombarded with alpha particles, gives rise to an emission of protons and forms an oxygen isotope of mass 17. In this book, however, we shall make no further use of this notation.

172. Proton Bombardment. — Protons were the first artificially accelerated particles to be used in bringing about a nuclear transformation. In England, Cockcroft and Walton obtained alpha particles by bombarding a lithium target with protons, in accordance with the equation

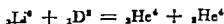


Although these experimenters used protons accelerated by some 150,000 volts and the transmutation can be brought about by less than 25 000 volts, the efficiency of such processes increases rapidly with the speed of the particles. For example, in one investigation it was shown that whereas for 250 000 volt protons there was one successful hit in 10^9 shots, for 500 000 volt protons, there were ten successful hits in the same number of shots. In many reactions it is desirable to have available particles speeded up by several million volts.

We conclude this section with two other examples of proton bombardment which explain themselves.



173 Deuteron Bombardment. — High speed deuterons, that is, nuclei of the atoms of heavy hydrogen have proved of the greatest importance in bringing about nuclear transformations. At this stage we give two examples. The first is described by the equation



Here, it will be noted, the lithium 6 isotope, on bombardment with deuterons, gives rise to alpha particles. This particular reaction is beautifully illustrated by Fig. 174 where *a* and *b* mark the paths of the two alpha particles ejected simultaneously in opposite directions.

To make these long trails, the alpha particles initially must have had a great deal of kinetic energy. As this energy is a direct result of the nuclear process which takes place, it should be evident that the equation does not tell the whole story. For a complete discussion consideration must be given to the energy involved, a question considered in section 184.

A second example of deuteron bombardment which the student can interpret himself is given by the equation



Other important examples will be given later.

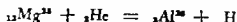


Courtesy P. I. Dow, R. T. N. W. Watson and The Royal Society

Fig. 174 *a* and *b* mark the paths of two alpha particles ejected simultaneously in opposite directions when a bombarding deuteron struck the nucleus of a lithium atom.

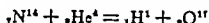
174 Artificial Alpha Particles.—By using helium in the dees of a cyclotron alpha particles with kinetic energy exceeding 15 million electron volts have been obtained. Since the energy of alpha particles from a radium preparation is of the order of 4 million electron volts, we see what a powerful tool the cyclotron is. Moreover not only can much faster artificial alpha particles be developed, but the intensities of the beams so obtained are the equivalent of huge amounts of radioactive materials.

The following is given as an example of the many nuclear transformations which have been brought about by the use of artificial alpha particles.



175 Discovery of the Neutron.—The discovery of the *neutron*, a particle of mass number 1 but without any electrical charge was the result of

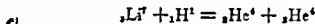
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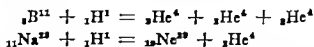
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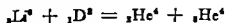


Although these experimenters used protons accelerated by some 150 000 volts and the transmutation can be brought about by less than 25 000 volts, the efficiency of such processes increases rapidly with the speed of the particles. For example, in one investigation it was shown that whereas for 250 000 volt protons there was one successful hit in 10^9 shots, for 500 000 volt protons, there were ten successful hits in the same number of shots. In many reactions it is desirable to have available particles speeded up by several million volts.

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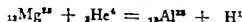


Courtesy P. I. Dow, R. T. E. Wilson and the Royal Society

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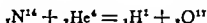
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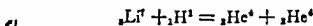
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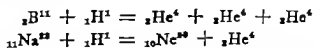
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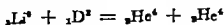


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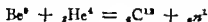


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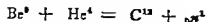
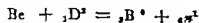
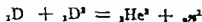
near which or through which the particle is passing. In consequence, electrons are pulled out of many of the atoms in the path of the particle the atoms are thereby ionized and the moving charged particle is gradually slowed down as its energy is thus expended. With an *uncharged* particle, however, no such strong electrical forces exist and the slowing-down process is very much less rapid. Indeed, direct hits on the nuclei of the atoms are mainly responsible for the absorption of such a particle by the medium through which it passes. The slowing-down process of an uncharged particle, therefore depends on two factors (1) the degree of closeness, and (2) the masses of the nuclei. Actually the absorption is much greater in a light substance than in a heavy because mass for mass, there are far more nuclei in the light than in the heavy substance. Moreover the colliding particle if of small mass, bounces off a very heavy nucleus with little loss of energy whereas on collision with a light nucleus, such a particle transfers much of its energy to the struck particle. The fact, therefore that lead is more transparent than light substances to the radiation in question is a strong argument in support of the hypothesis that this radiation from beryllium consists of a stream of neutrons, particles uncharged, whose masses are much less than those of the nuclei of lead atoms. If the mass of a neutron is of the same magnitude as a proton the neutron in a head-on collision against a proton gives up all its energy to the proton and the marked absorption of neutrons by substances containing hydrogen finds a ready explanation.

Chadwick, therefore, concluded that this extremely penetrating radiation consisted of a stream of neutrons generated according to the equation

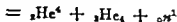


where ${}_0\pi$ is the symbol for a neutron

176 Other Methods of Producing Neutrons. — Subsequent work showed that neutrons are liberated in many nuclear reactions, but bombardment of certain substances by deuterons has proved particularly useful. We give three examples in the following summary of neutron producing methods.



or



certain experiments in which alpha particles from a radioactive source were the bombarding particles. In Germany Becker and Bothe, when bombarding certain substances with alpha rays from polonium observed, particularly from the element beryllium, the emission of a radiation sufficiently penetrating to pass through tolerably thick sheets of metal. This radiation they considered to be similar in nature to gamma rays.

Following up this work, in France, Joliot and his wife, the daughter of Madame Curie of radium fame, were able with more intense sources of alpha rays, to show (1) that this radiation could penetrate an inch or more of lead, and (2) that, when it struck a substance like paraffin wax (which contains a large amount of hydrogen) protons were ejected with great energy. Note the two steps in producing the protons. Alpha rays strike beryllium; beryllium emits this penetrating radiation supposedly of a gamma ray nature the radiation strikes the paraffin wax, and protons are ejected.

In England at Cambridge, a particle without charge and with the mass of a proton had been sought for more than once. As far back as 1920 Rutherford had made reference to the possible existence of a neutron and about the same time Harkins at Chicago had pointed out that the problem of building heavy nuclei from light was much simplified if particles of this nature were available as building bricks. Now Chadwick working at Cambridge saw that it was highly probable that at least part of this penetrating radiation from beryllium consisted of neutrons and he set out to prove it.

It was clear that the radiation in question knocked protons out of paraffin wax, and it was a simple enough matter to measure the energy of the expelled protons, by examining how far they traveled. When this was done it was seen that it was extremely unlikely that they were knocked out of the wax by a gamma ray. For this to be possible the gamma ray photon would have had to possess some fifty million electron volts of energy, an amount far in excess of any probable value for such radiation. On the other hand, if the radiation consisted of high speed material particles, each with a mass approximately the same as that of a proton the behavior of the emitted protons was exactly what was to be expected. The gamma ray hypothesis was something like assuming that a pellet of buckshot by striking a cannon ball could project it forward, whereas the (neutron) particle hypothesis made only the reasonable assumption that it was a case of one cannon ball being struck forward by another.

The ease with which the debatable radiation passed through thick layers of lead strongly suggested that the particles, if such they were, were uncharged. When a positively charged particle ploughs through matter there are strong forces of attraction between it and the negatively charged electrons in an atom

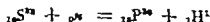
178. Protection against Neutrons. — From what has been stated in the previous section it will be evident that it is highly necessary to provide adequate protection against possible neutron bombardment. It should be equally clear that a substance like lead is practically useless as an absorbing material. Neutrons will pass through several feet of lead. In actual practice protection is provided by surrounding a neutron source with tanks of water, use being made of the slowing down of the neutrons by impacts against protons. After some twenty collisions, a five million electron volt neutron is slowed down to such an extent that its energy is only about one tenth of an electron volt. Certain nuclei strongly absorb slow neutrons. If boron for example, is added to the water in the tank, it becomes a still better absorbing layer.

179 Neutron Bombardment. — Because of the ease with which uncharged neutrons can come in contact with nuclei of atoms, this particle has proved particularly valuable in bringing about nuclear reactions. In this work, it has been shown that both fast and slow neutrons are highly effective in causing transformations. Here is one example in which an alpha particle is ejected as a result of the disintegration of the temporary compound formed when a neutron unites with a boron atom



This is an especially interesting reaction because Paneth and co-workers not only identified spectroscopically the small amount of helium manufactured but also measured the volume liberated when the source of neutrons acted for a measured time. Some idea of the delicacy of Paneth's measurements is obtained from the fact that he dealt with volumes of the order of one ten-millionth of a cubic centimeter.

An important reaction involving a product ${}_{12}\text{P}^{30}$ to which we shall again refer, is given by



A reaction like this, in which a proton is emitted as a result of disintegration after the coalescing of the neutron with a nucleus, must not be confused with the collision of a fast neutron with a proton. In the latter case energy is communicated to the proton and it goes ahead as a recoil particle.

An excellent illustration of the power of a colliding neutron to bring about disintegration is found in the fact that whereas with the fastest alpha particles available no disintegration had been obtained with elements of atomic number greater than 19 after the discovery of the neutron it was soon shown that

Although the cyclotron is the chief instrument for obtaining high speed particles, it is worth while noting that at the Mount Vernon Hospital, London, the $D + D$ reaction noted above has been used satisfactorily with an accelerating tube operated on 300,000 to 400 000 volts. "This plant has so far given an output of neutrons equal to that produced by 30 curies of radon plus beryllium "

177 Importance of the Neutron. — We have described somewhat in detail the steps leading to the discovery of the neutron as well as different methods of preparation because there is ample evidence that biologically neutrons are of very great importance. Although, as we have seen, a neutron being uncharged does not ionize directly, indirectly it may cause intense ionization in a very short distance. For example, in passing through tissue with its high percentage of hydrogen many neutrons are stopped (or slowed down) by direct hits (or less direct collisions) against protons. These protons then begin to move with the energy imparted to them by the neutrons, and being heavy charged particles cause intense ionization as they are slowed down. Since we have good reasons for believing that ionization is the primary cause of biological changes, it is only reasonable to expect strong biological reactions with neutron bombardment.

Direct evidence of this has been obtained in experiments which showed that neutrons were several times more effective in destroying malignant cells in rats than x rays, and also in retarding the growth of wheat seedlings. In this connection we quote from an article by Gray Read and Mottram in *Nature* (Sept. 1939) "Neutron energy thus appears to be about ten times as efficient as gamma radiation energy in its lethal effect on bean roots."

In a still more recent article in *Nature* (Jan., 1940) J. H. Lawrence writes "The intense beam of neutrons produced by the cyclotron has made it possible to investigate their biological effects on various objects such as bacteria, plants, *Drosophila* eggs, animal tumors and normal mammals. This new penetrating form of radiation has intense biological effects, even greater than x rays or gamma rays, on normal and tumor tissue, but when compared with x rays, selectively affects some tissues more than others. Experiments on animals indicating that neutrons are more destructive to neoplastic tissue than to normal tissue suggested their trial in cancer therapy

Careful experimenting alone can decide to what extent neutron bombardment may be valuable in the treatment of cancer. Already a beginning has been made at Berkeley California, the home of the first cyclotron and in due time valuable data will be collected there and at other centers.

dots representing ions look exactly the same as those obtained with beta rays and fast electrons. Moreover estimates of the energy of such particles, based on the measured curvature of their tracks (and the assumption that they are electrons) lead to values in agreement with observations of their ionization and their penetrating powers. We get into difficulties, however when we try to ascribe the trail of opposite curvature to either an alpha particle or a proton. This trail also looks exactly like that of an electron and not at all like the heavy continuous line representing the trail of an alpha particle or of a proton. If disregarding this similarity to the path of an electron the particle is assumed to be either an alpha ray or a proton and its energy is calculated making use of the amount of curvature values are obtained far too small to account for the observed penetrating power. All the evidence therefore, indicates that the trail is caused by a positively charged particle of mass comparable with that of an electron. When cosmic ray cloud track photographs were first taken no such particle was known to exist, but this was the conclusion to which Anderson in the United States, in 1932, and not long afterwards Blackett in England were driven. This new particle was given the name *positron*.

Another good example of the track of a positron is shown in Fig 168

Although the positron is, in many ways, the counterpart of the electron it differs from it in one important respect because unlike the ubiquitous stable electron the positron is an extremely short lived unstable particle.

The *mesotron* revealed its existence in expansion chambers as a track heavier than that of an electron or a positron but less heavy than that of a proton. It has now been definitely established that it is an unstable short lived particle, which may be either positive or negative having a mass of the order of 200 times that of an electron. For a while it was referred to as the heavy electron.

In concluding this brief reference to cosmic rays, it is interesting to note that there is evidence that the rays come in from outer space with energies exceeding a thousand million electron volts.

181. Artificial or Induced Radioactivity — In 1934 Mme and M Joliot, working in France found that aluminum foil which had been bombarded with alpha rays for a few minutes, emitted positrons after the bombardment had ceased. The foil could be removed from the source of alpha rays — taken into another room altogether — and when brought near a charged electroscope caused it to lose its charge just like a natural radioactive body. The aluminum soon lost its acquired radioactivity decreasing to half strength in about three minutes, but the effect was unmistakable. Aluminum can be made temporarily radioactive by bombardment with alpha rays. What exactly happens?

elements of high atomic weight, such as gold, were readily disintegrated. In this work the name of the Italian physicist Fermi is outstanding.

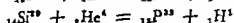
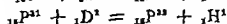
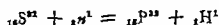
More recently a new type of atom-splitting, often referred to as the *fission* of heavy nuclei, has been brought about by the use of neutrons. For example, it has been shown that when a neutron collides with the nucleus of uranium, a disintegration takes place into two atoms, probably barium and krypton both of fairly high atomic weight. After the fission, there is evidence that each product emits neutrons. This reaction is of great interest and may possibly prove to be of economic importance because, as a result of a single fission energy of the order of 100 or 200 million electron volts is released. The possibility of harnessing this energy is discussed in section 185.

For the radiologist, the most important result arising from the nuclear reactions brought about by bombardment of atoms with neutrons and other particles, is the manufacture of artificial radioactive elements. Before discussing this important question however, a brief reference must be made to one or two new particles.

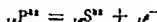
180 The Positron, the Mesotron, and Cosmic Rays. — In section 41 it was stated that at all times there are a few stray ions present in air. The study of the cause of the feeble conductivity arising from these ions led to the conclusion that the earth's atmosphere is traversed by a radiation of as yet unknown origin coming in "from out of the everywhere into here." This radiation is now called *cosmic rays*. Hundreds of investigations have been made and hundreds are in progress, concerning the nature of these rays. Although much information has been found the question of cosmic rays presents many problems still unsolved and in this text details would be out of place. As a result of these researches, two new particles have been discovered, the *positron* and the *meson* or *mesotron*. In the discovery of these particles cloud track photographs played an important part.

Figure 169 reveals a phenomenon which frequently occurs when a cosmic ray strikes a substance like the metal plate. As is seen in this photograph a shower of electrified particles, originating as a result of the impact of a cosmic ray has emerged from a center marked *C* in the material surrounding the cloud track chamber. When this photograph was taken the particles had to traverse a magnetic field, and hence the curvature in opposite directions strongly suggests that there are two kinds, one with a positive charge, the other with a negative. The only known negatively charged particle is an electron but we have become familiar with two positive particles, alpha rays and protons. The assumption that the path curved in one direction is caused by an electron is greatly strengthened by the appearance of the trail, because the little

following equations describe three of the several ways in which it can be prepared.



When ${}_{16}\text{P}^{32}$ disintegrates, beta rays are emitted, hence ${}_{16}\text{S}^{32}$ must be the final stable product, in accordance with the relation

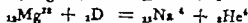
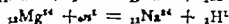
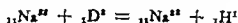


The radioelements listed in Table XXXII are taken from an article in *Nature* (Jan 27 1940) by J H Lawrence of the Radiation Laboratory, University of California, and show some of the isotopes used in biological investigations at that institution. In the latest available complete list of radioelements (Jan. 1940) more than 330 are noted.

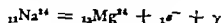
TABLE XXXII

Radioelement	Radiation	Half-Period
Hydrogen, H^3	beta	150-170 days
Carbon, ${}_{6}\text{C}^{14}$	positron and gamma	20.5 mins.
Sodium, ${}_{11}\text{Na}^{24}$	beta and gamma	14.8 hours
Phosphorus, ${}_{15}\text{P}^{32}$	beta	14.3 days
Sulphur, ${}_{16}\text{S}^{35}$	beta	88 days
Chlorine, ${}_{17}\text{Cl}^{36}$	positron and gamma	33 minutes
Potassium, ${}_{19}\text{K}^{40}$	beta and gamma	12.4 hours
Calcium, ${}_{20}\text{Ca}^{45}$	beta and gamma	180 days
Iron, ${}_{26}\text{Fe}^{59}$	beta and gamma	47 days
Bromine, ${}_{35}\text{Br}^{80}$	beta and gamma	34 hours
Iodine, ${}_{53}\text{I}^{131}$	beta and gamma	13 days

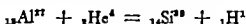
We have already indicated several ways in which ${}_{11}\text{Na}^{24}$ can be manufactured, and shall describe details about the preparation of only one more, ${}_{11}\text{Na}^{24}$. This is manufactured in the following ways.



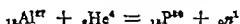
When radiosodium²⁴ disintegrates, with a half-period of 14.8 hours, ${}_{11}\text{Mg}^{24}$ is the stable product and beta and gamma rays are liberated. In symbols we write



An examination of the transmutation products resulting¹ from the bombardment of aluminum with alpha rays, shows that *during the bombardment* sometimes protons are emitted, sometimes neutrons and positrons. The proton emission is readily explained by the transformation



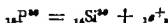
To account for a neutron emission, the following transmutation must take place.



In this case, the products of the transformation are a neutron and an element which must be phosphorus, because its atomic number is 15. Phosphorus is a well known element with a stable isotope of mass number 31, but it has no known stable isotope with mass number 30. Mm. and M. Jolot, therefore, concluded that this isotope of phosphorus is unstable or radioactive, emitting positrons when it 'explodes.' What happens then is this. The original bombardment of the aluminum manufactures a certain amount of ${}_{13}\text{P}^{30}$. On ceasing fire with the alpha rays, the foil is removed and embedded in it are these new unstable or radioactive atoms. When they explode, they shoot off positrons.

Since a positron has an almost negligible mass and one unit positive charge, the nucleus left behind after the explosion has practically the same mass as before, but an atomic number one less. In the case of ${}_{13}\text{P}^{30}$ the nucleus left, therefore, must have an atomic number of 14 hence it must be silicon.

We may write



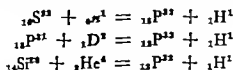
where ${}_1\text{e}^+$ is the symbol used for a positron.

The half-period of P^{30} is a little less than three minutes.

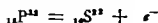
To distinguish an unstable, radioactive isotope of an element from a stable one, particularly when the element occurs in nature only in its stable form, the prefix *radio* may conveniently be used. Since, however the same element may have more than one radioactive isotope the mass number should also be specified. The element phosphorus, for example, has a radioactive isotope of mass number 32 as well as of 30.

Radiophosphorus³² or ${}_{15}\text{P}^{32}$, is of much greater importance to the radiologist than ${}_{15}\text{P}^{30}$ because its half-period of 14.3 days is so much longer. The fol-

following equations describe three of the several ways in which it can be prepared.



When ${}_{13}\text{P}^{32}$ disintegrates, beta rays are emitted, hence ${}_{16}\text{S}^{32}$ must be the final stable product, in accordance with the relation

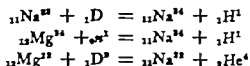


The radioelements listed in Table XXXII are taken from an article in *Nature* (Jan 27 1940) by J H Lawrence of the Radiation Laboratory University of California, and show some of the isotopes used in biological investigations at that institution. In the latest available complete list of radioelements (Jan. 1940) more than 330 are noted.

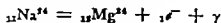
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Bromine, ${}_{35}\text{Br}^{80}$	beta and gamma	34 hours
Iodine, ${}_{53}\text{I}^{131}$	beta and gamma	13 days

We have already indicated several ways in which ${}_{13}\text{P}^{32}$ can be manufactured and shall describe details about the preparation of only one more, ${}_{11}\text{Na}^{24}$. This is manufactured in the following ways.



When radiosodium²⁴ disintegrates, with a half period of 14.8 hours, ${}_{12}\text{Mg}^{24}$ is the stable product and beta and gamma rays are liberated. In symbols we write



Radiosodium²⁴ may readily be made in quantities which are the equivalent of thousands of dollars worth of radium. These artificial radio-isotopes are important, however, not only because they supplement natural radioactive substances as sources of radiation, but also because of their use as indicators or tracers. This question we discuss in the next section.

182. Radioactive Indicators. — The use of radioactive materials as indicators depends on two facts. (1) The ionization method of detecting and measuring small quantities of a radioactive substance is so sensitive that it is possible to measure quantities millions of times less than the smallest amount detectable even by the spectroscope. Hevesy and Paneth who were pioneers in the use of radioactive elements as indicators, state that whereas "spectroscopy can often not only detect, but even measure, much smaller amounts, down perhaps to 10^{-6} or 10^{-10} gm. only the methods of radioactivity are able exactly to determine quantities of matter of the order of, say 10^{-17} gm."

(2) Stable isotopes and unstable or radioactive isotopes of the same element have identical chemical properties, and, therefore, cannot be separated by chemical means.

Now long before the discovery of artificial radioelements it was realized, notably by Hevesy and Paneth that if a small amount of a radioactive isotope was mixed with a large amount of a stable isotope of the same element, the activity of the radioactive portion would reveal the presence of the whole quantity. Bismuth and radium E, for example, are isotopes with the same atomic number 83 and if these substances are mixed, it is impossible to separate them by chemical means. But, wherever the mixture is, its presence can be detected by the signals which the unstable atoms of radium E send out in the form of ionizing beta radiations. Moreover because of the extreme sensitivity of the ionization test, only a very small amount of the radioactive tracer or indicator is needed. This particular example has been given because bismuth is used in the treatment of syphilis, and by the addition of radium E, it was possible to investigate the rate at which different bismuth compounds are resorbed after injection (Hevesy and Paneth).

The discovery of the comparative ease with which it is possible to manufacture radioactive isotopes of elements present in plants and animals has naturally led to their use in biological and physiological investigations. In the preceding section a list of radioelements used in biological investigations has already been given and to two of these we now make a brief reference. Because of its fairly long half-period and its importance in body metabolism radio-phosphorus²⁵ is the indicator which so far has been most frequently used in

biological investigations. A small amount of the radioactive element, mixed with sodium phosphate, is introduced into the body by the mouth and the subsequent behavior of the phosphorus traced. It is not the object of this book to go into details concerning the results of such investigations, but it is interesting to note that it has been shown that the role of phosphorus in bones, for example is a dynamic process that is, atoms of this element are constantly being replaced by the arrival of fresh atoms. As another illustration we quote again Hevesy and Paneth "Hence, from the presence of radioactive phosphatides in the brain tissue of fully grown animals after the intake of radioactive sodium phosphate we can conclude that these tissues, contrary to general assumption are constantly regenerated"

The same methods applied to plants have shown that in the leaves of maize and sunflowers, phosphorus atoms wander about, the same atom moving from one leaf to another in the course of a few days.

Although the half period of radiosodium²⁴ is much shorter than that of P^{32} it also has proved useful as an indicator. Common salt, to which a little of ^{24}Na has been added can be detected in a hand ten minutes after it has been swallowed and when a solution of common salt is injected intravenously in one hand, twenty seconds later sodium appears in the other hand. Another investigation, in which rabbits were used has provided evidence that there is a threefold concentration of sodium in the heart as compared with other tissues.

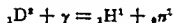
A glance at Table XXXII shows that isotopes of many of the elements listed there are present in the human body. From the brief account which has been given above it should be evident that investigations using these elements as indicators are certain to provide valuable biological physiological, and even pathological information.

183. Gamma Ray Bombardment. — In sections 109 116 118 and 121 reference was made to the view that radiation must be thought of as existing in energy units called quanta. It will be recalled that for radiation of wave length λ , a quantum has the value $\frac{h \times c}{\lambda}$ where h is Planck's universal constant of magnitude 6.56×10^{-27} erg \times sec. and c represents the velocity 3×10^{10} cm per second with which all electromagnetic waves travel. It was pointed out also that sometimes it is necessary to think of radiant energy traveling through space as photons, each photon having a quantum of energy. Using this point of view for example, we saw in section 118 that it was easy to explain the production of recoil electrons when x rays are scattered. In section 121 it was also shown that, if we express in electron volts the energy of a

photon of radiation of wave length λ angstroms, we obtain the result

$$\text{Energy of photon} = \frac{1.23 \times 10^4}{\lambda(\text{angstroms})} \text{ electron-volts.}$$

For a gamma ray of wave length 0.0056 angstrom, one of the shortest emitted by radium C, this gives the value 2.2×10^6 e.v., that is, over two million electron volts. If, now we keep in mind that photons may have energy values as large as this, it should not be surprising to learn that nuclei of some atoms can be disintegrated by gamma ray bombardment. We note two examples. (1) Using gamma rays from thorium C', of magnitude 2.62 million e.v., Chadwick and Goldhaber disintegrated deuterons into protons and neutrons, in accordance with the equation

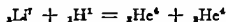


(2) Neutrons may be generated by bombarding beryllium with gamma rays, provided their energy exceeds 1.4 million e.v.

Since amounts of energy far in excess of two or three million electron volts are necessary to disintegrate the great majority of stable isotopes, there are not many examples of disintegration by gamma rays.

184 Mass and Energy — The work on disintegration and transmutation has shown that the nuclei of atoms must be complex in structure. In present day physics one of the important problems is the elucidation of this structure. It is not our purpose to go into details about the information which so far has been obtained, but there is one question relating to nuclear structure and nuclear transformations which is so fundamental that some explanation of it must be given. This has to do with the equivalence of mass and energy.

In section 171 it was pointed out that, in equations dealing with nuclear reactions, the sum of the mass numbers on each side of the equation must be the same. This, however, is true only to a first approximation. If use is made of the accurate values of atomic weights found by the mass spectrograph a few of which are listed in Table V section 48 a very slight discrepancy between the sums is found. As an example consider again the reaction



If we set down in a kind of balance sheet, the accurate mass values, we see at once that the sum on the right side of the equation is distinctly less than the sum

BEFORE	
Mass of Li^7	= 7.0182
Mass of H^1	= 1.0081
Sum	= 8.0263

AFTER	
Mass of He^4	= 4.0040
Mass of He^4	= 4.0040
Sum	= 8.0080

on the left. The discrepancy is not great, being only 0.018 but it is far too large to be described to experimental error. In the transaction apparently mass has been lost. What has become of it?

The answer to a question of this kind had already been given by Einstein who showed that *every form of energy has an equivalent mass*. It is a wrong although a very common idea, to consider mass and matter synonymous. It is perfectly correct to state that inert matter has mass, but the converse is not necessarily true, because all mass is not associated with matter. Energy too has mass. A photon, for example has mass; and the mass of a proton is greater when it is moving than when it is at rest by the mass equivalent of its kinetic energy.

In symbols, Einstein's law is written

$$E = mc^2 \quad \text{or} \quad m = \frac{E}{c^2}$$

where E represents the amount of energy, c is the velocity of light, and m the equivalent mass. Let us put the matter in numbers.

The mass of a hydrogen atom = 1.66×10^{-24} gm. and $c = 3 \times 10^{10}$ cm per sec. If therefore, it was possible to annihilate a hydrogen atom although inert matter would disappear the mass would now be associated with an amount of energy given by

$$E = 1.66 \times 10^{-24} \times 9 \times 10^{20} \text{ ergs.}$$

If this energy is expressed as V electron-volts, then we write (see section 35)

$$\frac{V}{300} \times 4.8 \times 10^{-10} = 1.66 \times 10^{-24} \times 9 \times 10^{20},$$

from which

$$V = 933 \text{ million e.v.}$$

Thus, we may state that the disappearance of about 1 unit of matter on the atomic weight scale should release about 930 million e.v. hence the disappearance of 0.001 of a unit releases about 0.93 million e.v. Approximately we may use 1 million e.v. as the equivalent of 0.001 of an atomic weight unit.

On this view then *conservation of mass holds only if we include the mass*

equivalent of any energies involved in a transaction. The truth of this was proved by direct experiment for the reaction ${}_3\text{Li}^7 + {}_1\text{H}^1 = {}_2\text{He}^4 + {}_2\text{He}^4$. In one experiment it was shown that when the bombarding proton had 300,000 e.v. of kinetic energy each of the emitted alpha particles is ejected with 8.7 million e.v. of kinetic energy. When these energy values are taken into consideration and Einstein's law is applied, there is no discrepancy between the total mass on one side of the equation and the total on the other. Our balance sheet now is written.

BEFORE

Mass of lithium ⁷ atom	= 7.0182
Mass of bombarding hydrogen ¹ atom	= 1.0081
Mass equivalent of 300,000 e.v.	$= \frac{300,000}{933,000,000} = .0003$
Total	<u>8.0266</u>

AFTER

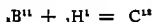
Mass of 2 helium atoms = 2×4.0040	= 8.0080
Mass equivalent of 8,700,000 e.v.	$= \frac{8,700,000}{933,000,000} = .0093$
Mass equivalent of 8,700,000 e.v.	$= .0093$
Total	<u>8.0266</u>

185 Energy from Destruction of Matter — If man could destroy matter and harness the energy released, the consequences would be amazing. The annihilation of a pellet of coal weighing an ounce would release enough energy to provide the electric power requirements of a quarter of a million people for one year if we assume a monthly bill of \$5.00 and a rate of 2 cents per kilowatt hour.

The results of the proton bombardment of lithium seem to suggest that the release of atomic energy in this way is more than a possibility. A single 0.3 million e.v. proton brings about the release of two alpha particles, each with 8.7 million e.v. and this looks like a profitable business. The profit, however, is more apparent than real because, for every proton which hit a lithium atom, some ten million were fired without making a direct hit at all. The energy expended in shooting this large number is entirely wasted, and if we take it into consideration the release of energy by transmutation of this sort is a very inefficient process. The fission of uranium to which a brief reference was made in section 179 suggests a much more likely means of utilizing the energy released when a nuclear reaction takes place. When slow neutrons collide with U^{235} fission results with the liberation of neutrons and of enormous quantities of energy. If the U^{235} is surrounded by water the liberated neutrons are slowed down and hence, provided sufficient U^{235} is present, a chain re-

action can go on with continuous liberation of energy. Early in 1940 investigations in the United States isolated small but measurable quantities of U^{235} from the other isotopes of this element. The possibility of utilizing commercially energy released in this way then became more than a fantastic dream and the daily press gave considerable prominence to this new source of power. U^{235} cannot be produced without the expenditure of energy, however, and it has yet to be demonstrated that this nuclear reaction is commercially feasible.

186. Emission of Gamma Rays in Nuclear Reactions.—In the proton-lithium reaction the form of the energy released was kinetic, but this is not the only kind which may appear. Sometimes radiant energy is released when a nuclear reaction takes place. For example, when protons bombard boron¹¹ gamma rays are emitted as a result of the transmutation



Since the mass of $\text{B}^{11} = 11.0128$
 and the mass of $\text{H}^1 = 1.0081$
 or the total $= 12.0209$
 and since the mass of C^{12}
 $= 12.004$

we see that the lost mass, or more accurately the loss of mass associated with matter $= 0.017$ unit. Hence, energy is released to the extent of 17×0.93 or about 16 million e.v. Experimentally when this reaction takes place an emission of gamma rays is observed, with energy reaching a maximum value of 16.6 million e.v. From observation and measurement of the energy of gamma rays emitted in such a reaction valuable information is obtained about the various states or conditions in which the nucleus of a stable atom may exist.

This emission of gamma rays must not be confused with the gamma radiation from a radioactive element. In that case an unstable nucleus is formed as a result of the nuclear reaction. When subsequently such a nucleus explodes because of its instability gamma rays are sometimes emitted.



Courtesy Mima and M. Joliot

FIG. 175 An electron-pair. The two tracks curved in opposite directions and emerging from the same point are the paths of positron and an electron created by the disappearance of a gamma ray.

A striking example of the equivalence of energy and mass is the disappearance of a gamma ray photon and the creation of an electron and positron. When in a region close to a nucleus, a photon may disappear to give rise to an electron pair. Figure 175 is a cloud track photograph illustrating this phenomenon.

187 Structure of the Nucleus.—The disintegration of a deuteron into a proton and a neutron is direct evidence that the nucleus of an atom of deuterium is made up of one proton and one neutron. From both theoretical and experimental considerations the view is now generally held that nuclei of all atoms are made up of protons and neutrons. Nitrogen¹⁴, for example, has 7 protons and 7 neutrons; helium⁴ or an alpha particle, 2 protons and 2 neutrons.

In radioactive isotopes, the nuclei are unstable, and sooner or later they disintegrate spontaneously. The nuclei of most stable isotopes, however, are difficult to disintegrate. It follows that the forces holding protons and neutrons together at extremely small distances must be very great. Little is known about these forces and the reason for such strong attractions, but it is not difficult, in some cases, to show how strong is the binding energy holding the particles together in the nucleus. As an example, consider an alpha particle, whose mass is 4.004 units. Since the mass of two protons and two neutrons is approximately 4×1.008 or 4.032 units, when these four particles are united in a single nucleus, there is a loss of $4.032 - 4.004$ or 0.028 unit. This represents an amount of energy equal to 28×0.93 or about 26 million e.v. Hence, to disintegrate an alpha particle would require this amount of energy.

With the intensive research being done in the field of nuclear physics, our knowledge of the nucleus is being rapidly extended and it may be stated with confidence that the future will reveal important developments.

CHAPTER XVI

HIGH FREQUENCY CURRENTS

188. **Classification of Currents.** — In Chapter X a brief reference was made to the electrical waves which are radiated from a circuit carrying rapidly oscillating currents. Since currents of this kind are used in electrotherapy in the concluding chapter of this book a short account is given of the means by which such rapid oscillations are developed. At the outset we summarize the various types of currents with which a radiology student should be familiar. There is first of all the broad classification used by the practical electrician into D.C. and A.C., that is, into unidirectional and alternating currents. Under D.C. we include the following:

(1) The steady current which is maintained in a simple circuit by a constant source of E.M.F. such as a storage battery or a D.C. dynamo or any good cell. Such a current at one time was designated *galvanic*, the term *galvanism* being applied to the use of such currents.

(2) *Intermittent* unidirectional current, such as that through a self rectified x-ray tube or a tube operated by a transformer with mechanical rectifier.

(3) *Pulsating* direct. — This kind is somewhat similar to an intermittent current, except that in pulsating the current need not necessarily drop to zero between places of maximum intensity. A pulsating current can be obtained by the use of a mechanical device whereby resistance is regularly taken out of a circuit or added to it.

(4) *Primary faradic* — This is the name sometimes given to the current in the primary of an induction coil controlled by a hammer break. This also is an intermittent current, but one which is characterized by the abruptness with which the current drops to zero value. (See Fig. 13.) Due to this abruptness, a marked stimulus may be applied to a muscle or a nerve by the use of such a current.

(5) *Secondary faradic* — Currents through the secondary of an induction coil can be classified as direct, if the magnitude of the induced E.M.F. on make is so small that no appreciable inverse current flows. In a good coil this should be the case. Frequently however inverse current is present, and if so, secondary faradic should more properly be classified under A.C.

The following can properly be classified as A.C

(1) The gradually changing *sinusoidal* current represented by the smooth curve of Fig 4 Commercial A C of 25 or 60 cycle per second approximates to this kind.

(2) High Frequency The term *high* is applied when the frequency of alternating currents reaches a value of the order of 100,000 cycles per second. Frequencies of a million and more cycles per second are quite common, and it is now not unusual to use values as high as 300 million or even higher. When such currents pass through tissue, there is not the marked stimulus resulting in muscular contraction or painful sensation which faradic or even low frequency currents cause. High frequency currents, however, have the important applications noted below.

189 The Generation of Damped H.F. Currents. — H.F. currents may be divided into two classes according as the oscillations are damped or undamped. First we consider the generation of damped currents.

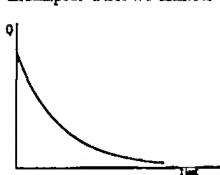


FIG. 176. Graph representing the aperiodic discharge of a condenser

When a condenser is charged, and then discharged, the discharge current is one of two kinds. If the terminals of the condenser are connected by a fairly high resistance a steady direct but gradually decreasing current flows until the condenser is completely discharged. This type of discharge, the *aperiodic*, is represented by the graph in Fig 176. If the resistance is low an oscillatory discharge, as represented by Fig 177 takes place. The reversals of current mean that

the condenser is discharged recharged in the opposite sense, discharged again, and so on the process continuing until the energy originally stored is ultimately dissipated in heat, and, sometimes, in radiation. In an ideal arrangement with negligible resistance, no heat would be developed, and the oscillations would continue for a long time — not indefinitely however because, as we shall see later radiation of electromagnetic waves takes place when the oscillations are sufficiently rapid.

An almost exactly analogous phenomenon takes place with an oscillating simple pendulum. If the "bob" of the pendulum is drawn to one side and then released, oscillations are executed until the original potential energy communicated to the system has all been dissipated in heat as a result of mechanical friction between the moving bob and the air. During the time that the oscillations are taking place, a constant exchange is going on between the potential

energy (P.E.) of the displaced bob and its kinetic energy (K.E.) At the end of each half oscillation the P.E. is a maximum and the K.E. zero, whereas at the middle position the opposite is true. Because of the small air resistance, this interchange goes on for some time before finally all the original P.E. is converted to heat.

Mathematical treatment of the oscillations in both the mechanical system and the electrical shows that the analogy may be pushed still further. Resistance is akin to friction and current to the velocity of the pendulum bob.

When the bob is in its lowest position where its velocity is a maximum its inertia causes it to overshoot the mark and to store up P.E. on the other side. So too when a condenser has been momentarily emptied, because of inductance, the current continues to flow and so the condenser is charged in the opposite sense. It will be recalled (see section 6) that whenever a current in a circuit is changing an induced E.M.F. or an E.M.F. of inductance is present which opposes the change. Moreover the greater the inductance of the circuit, the greater the magnitude of this opposing E.M.F.

Hence we may consider inertia and inductance as analogous quantities. In a mechanical system the greater the inertia of a body the greater its tendency to keep on moving when in motion in an electrical circuit the greater the inductance, the greater the tendency of a current to persist once it is started.

When these facts are put in mathematical language, exactly similar equations are set up for the mechanical and the electrical systems. From such equations

it is not difficult to show that, if $R < \sqrt{\frac{4L}{C}}$, where R is the resistance in ohms,

L is the inductance in henries, and C is the capacity in farads, an oscillating discharge takes place and that, for low values of R the frequency of the oscillations is given by

$$f = \frac{1}{2\pi\sqrt{CL}}$$

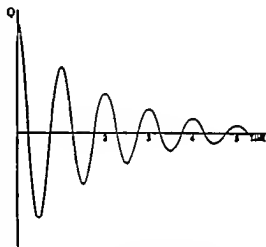


FIG 177 Graph representing the damped oscillatory discharge of a condenser

For example, if $C = 0.002$ microfarad, and $L = 1.27 \times 10^{-6}$ henry, f comes out to be nearly one million cycles per second.

It will be noted that, the greater the value of L and the greater C , the smaller the value of f or the lower the frequency. As far as L is concerned this is just what we should expect, because, as we have noted above, the greater the inductance, the greater the force resisting changes, or the more "sluggish" the current is. As far as C is concerned it is not difficult to understand why an increase in C should slow down the oscillations. Since at any instant, the voltage across the condenser $= Q/C$, it follows that the larger C the longer the time it takes for this potential difference to reach its maximum value during a half-cycle. For very rapid oscillations, then, both C and L should be small.

190 Experimental Demonstration of High Frequency — Suppose a Leyden jar of capacity C is joined to the terminals A B of a Wimshurst machine, somewhat as shown in Fig 178. When the machine is operated,

a charge piles up on each of the condenser plates until a potential difference (Q/C) develops which is sufficiently high to cause a spark to jump the gap AB . Because of the intense ionization associated with the spark, the gap becomes temporarily a region of low resistance, and an oscillating discharge of the condenser takes place. If this spark is examined in a revolving mirror, it is seen as a succession of flashes, not a single spark. By using an oscillograph, it may be shown in a still better way that the current when the condenser is discharging is oscillatory. Actually the oscillograph record shows a curve similar to that of Fig 177.

FIG. 178. The condenser C is charged by being connected with the terminals A and B of a Wimshurst machine.

If fairly high values of L and of C are used, it is possible to take readings in the laboratory from which a plot of the oscillatory discharge may be made, provided some means, such as the *Webster Drop Chronometer*, is available for measuring very small time intervals. With such a device, it is possible after charging a condenser, to measure with a ballistic galvanometer the charge left in it after each of a series of short but gradually increasing time intervals during which the condenser is allowed to discharge. The writer has recently examined the laboratory report of a group of students who had obtained in this way an excellent oscillatory curve using $C = 1$ microfarad and $L = 0.76$ henry.

191 Primary Tesla Circuit. — When a single complete discharge takes place with an arrangement like that of Fig. 178 the oscillations are heavily damped even with small resistance, and the total number of cycles is small. To make practical use of high frequency currents, a succession of discharges must be available. This is readily accomplished by any arrangement which recharges the condenser nearly as fast as it is discharged. A common arrangement is shown in Fig. 179 where *P* and *S* represent the primary and secondary of a step-up transformer. *A* and *B* are the terminals of a spark gap. *C* is a condenser and *L* an inductance. A few turns of heavy copper wire make a convenient inductance for many experiments. Since the plates of the condenser are always in electrical contact with the terminals of the secondary of the transformer the condenser is repeatedly recharged after each complete

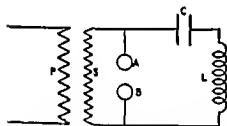


FIG. 179 The primary Tesla circuit, an arrangement for obtaining a succession of damped high-frequency oscillations.

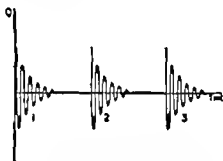


FIG. 180. The kind of high-frequency currents obtained with the arrangement shown in Fig. 179

discharge in the oscillatory circuit *BACL* and a succession of oscillation pulses is obtained. Figure 180 shows the nature of current in the oscillatory circuit with such an arrangement.

To the ear it seems as if continuous sparking were taking place, but actually the off-period that is, the interval between the pulses 1 and 2, 2 and 3. Fig. 180 may be many times longer than the actual time oscillations are taking place during a single pulse. For example, a small transformer operated on 60 cycles per second, might recharge the condenser every half-cycle that is, every $1/120$ of a second. If, then the frequency of the oscillations in the circuit *BACL* were a million per second, and there were 10 in a single pulse the total time of a pulse or a complete discharge would be $\frac{10}{1,000,000}$ or $\frac{1}{100,000}$ of a second, a time many times shorter than $1/120$ of a second, the interval between pulses.

Using such a circuit, one can show some striking experiments which demonstrate indirectly the existence of high frequency currents in the coil L . For example, if a tube containing the gas neon at low pressure is brought near this coil, or indeed, placed near almost any part of the oscillating circuit, the bright red luminous discharge characteristic of neon takes place in the tube. If one uses a carefully evacuated bulb into which a few drops of mercury have been distilled and the coil L consists of three or four turns of heavy copper wire wrapped around the center of this bulb, a brilliant discharge in the form of a ring occurs if the bulb is warmed to a suitable temperature.

A striking contrast to the mercury discharge is provided by using a bulb into which a little iodine has been distilled. If the vapor pressure of the iodine is regulated by having attached to the bulb a side tube immersed in ice and water one obtains a brilliant greenish-pink ring discharge when the gap AB is a few millimeters wide, and a less bright yellow ring for a much shorter gap.

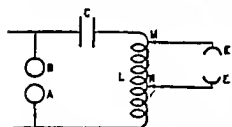


FIG. 181. An arrangement sometimes used in one type of diathermy.

These luminous discharges provide evidence of the rapid high frequency currents in the coil L . Rapidly changing currents mean equally rapidly changing magnetic fields in the neighborhood of the coil. But, whenever a magnetic field is changing, there is an induced E.M.F. whose magnitude is greater the greater the rate of change of the field. Hence, in the region near the coil or within a gas or a vapor contained in a tube placed within the coil, there exists an induced E.M.F. sufficiently great to cause a current in the gas, a current which is made evident by the luminosity.

192. Diathermy with Damped Oscillations.—In medicine one of the commonest uses of high frequency currents is to develop heat in tissue, as is done in *diathermy*.

In one simple arrangement, electrodes E and E , Fig. 181 are attached by means of conductors to points M and N in the coil carrying the currents. The electrodes are made of pliable metallic material which are frequently enclosed in a rubber casing. In use, the electrodes fit tightly against a protecting layer of woollen material in contact with the skin of the patient. With such an arrangement heat is developed in the tissue which provides the conducting path between the electrodes, a sensation of warmth being all that is felt by the patient. By making one of the electrodes of small area, it is possible to concentrate the heat locally.

In diathermy with damped oscillations, the intensity of the treatment can

be controlled by altering the length of the spark gap. The shorter the gap the smaller V the potential difference between the condenser plates, when a spark takes place. Since Q the charge stored in the condenser is equal to CV it follows that the quantity of electricity taking part in discharge and hence the average value of the current, is less, the smaller the gap.

Sometimes instead of attaching electrodes directly to two points on the oscillating circuit, a secondary circuit is *coupled* with the primary oscillating circuit, somewhat as shown in Fig. 182. Due to the coupling of the coils L and L_1 currents are induced in the circuit $L_1 C_1 E E_1$, the frequency of the induced electromotive force being the same as that of the oscillations in the primary. The intensity of the currents induced in the secondary circuit depends to a marked degree on whether or not the circuit $L_1 C_1 E E_1$ is *tuned* or in *resonance* with the primary circuit. The student will recall that when regular periodic impulses are applied to a system capable of oscillating the oscillations set up are of very high amplitude if the period of the impulses is the same as the natural period of the oscillating system. When this is the case the system is vibrating or oscillating in resonance with the external periodic impulses. The oscillating currents induced in the circuit $L_1 C_1 E E_1$ have their greatest intensity then when the natural period of this circuit is the same as that of the primary circuit. Since this natural period depends on the capacity (and the inductance) tuning to resonance is conveniently accomplished by making C_1 a variable condenser. To measure the intensity of the high frequency currents, as well as to indicate when resonance has been obtained an ammeter A may be placed in the circuit.

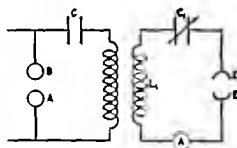


FIG. 182. A diathermy arrangement which uses a secondary circuit coupled with the primary Tesla.

193 Secondary Tesla Circuit. — The arrangement shown in Fig. 179 is sometimes called the primary Tesla circuit in honor of Tesla, one of the pioneer workers with high frequency currents. When high voltage as well as high frequency is wanted a secondary Tesla circuit is added. A common arrangement consists in coupling with the primary coil L a solenoidal coil L_1 of many turns of fine wire as in Fig. 183. If one end of L_1 is grounded, sparks several centimeters long will jump from the other end to a grounded conductor. Because of the high frequency of the currents, one may safely allow the sparks to jump to one's hand, or better to a piece of metal held

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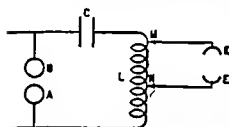


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In diathermy with damped oscillations, the intensity of the treatment can

means of the battery *B*) and to examine the variation of the current to the plate when the grid potential is given a series of values, both positive and negative. The graph of Fig 185 shows the general nature of the result obtained when such an experiment is carried out. Note the following

(1) For negative potentials greater than *OA* there is no plate current. The actual value of *OA* is considerably less than the plate potential. For example, in a tube examined in a laboratory class by a student, for a plate potential of +70 volts, *OA* was -22 volts.

(2) The main portion of the curve is almost linear in some tubes exactly so in others somewhat curved. This is the important part of the curve because normally the potential of the grid or its *bias* is such that the tube is operated on this portion of the curve.

(3) Saturation can be obtained, as in the diode, but it requires a fairly high positive grid voltage, and in using a triode as an oscillator (or a detector) it must be avoided. In making characteristic curves similar to that of Fig 185 it is really not necessary to extend the graph to this stage.

(4) By using a series of different plate voltages, a corresponding series of characteristic curves can be obtained. From an examination of these curves, the very important fact emerges that a small change in grid potential may bring about the same change in plate current as a much larger change in plate voltage. For example, in the case of the tube mentioned in (1) above, the student found that, with constant grid potential, a change of 30 volts in plate potential caused a change of 21 ma. in the plate current, but, at constant plate potential, a change of only 8.25 volts on the grid brought about the same change in plate current.* In other words, because of its proximity to the filament, the grid exercises a powerful control over the plate current. Its nearness to the filament makes it extremely efficient in attracting or repelling electrons, whereas its open mesh nature allows most of the electrons to pass through and reach the plate.

Because of the almost negligible inertia of electrons, this grid control has a very important consequence. If for any reason the potential of the grid

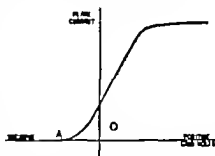


FIG. 185 Graph showing the variation of plate current in a triode valve with variable grid and constant plate potentials.

* From the ratio $\frac{30}{8.25}$ or 2.5 we obtain what is called the *amplification factor* of this tube.

tightly in the hand * In the equipment frequently used, L is a ring or short solenoid of a few turns of heavy wire, and L_1 is placed inside L

In fulguration, by attaching a flexible conductor to the secondary coil, such sparks may be directed and used in localized treatment.

194 The Triode Valve. — In order to give even the simplest explanation of how undamped high frequency currents are obtained, it is necessary to amplify somewhat the work previously given regarding the passage of electrons from a hot filament across an evacuated tube. The student is asked to recall the graphs given in Fig 53 and Fig 76 which show the way in which the current across a hot filament x ray tube or rectifying valve varies with the applied voltage, at constant filament temperature. This type of curve

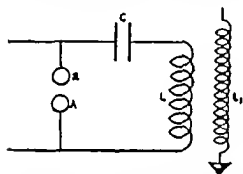


FIG. 183. High frequency currents of high potential are developed in the secondary coil L_1 if it is made of many turns.

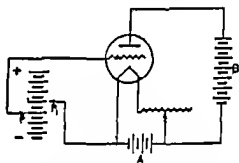


FIG. 184. Circuit for examining the effect of grid potential on the plate current in a triode valve.

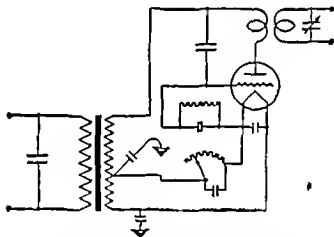
applies to any *diode* valve, that is, a highly exhausted tube with filament and anode.

In the *triode* valve, in addition to the filament which liberates electrons when heated, and the plate or anode a *grid* constitutes a third element. In the valve diagrams appearing in Figs. 184 186 and 187 the grid is represented by the central wavy line but actually it is a spiral of fine wire, or a wire mesh in close proximity to the filament. The anode or plate more or less surrounds the grid. To demonstrate the function of the grid, a circuit such as that illustrated in Fig 184 may be used. With this arrangement by varying the position of the contact P the potential of the grid with respect to P_1 and hence with respect to the filament can be made either positive or negative. It is possible then to maintain the plate at a constant potential (by

* It is not wise to do this when using the undamped high frequency currents described in section 195

compensation for ohmic and other losses in the circuit so that the system behaves as if it possessed zero resistance, and an oscillation once started in it, persists. (Appleton)

By this principle of retroaction *continuous* undamped oscillations are maintained. In actual practice there are many different circuits employing this principle in one way or another. Figure 187 for example shows the connections for a Hartley oscillating circuit one which has been extensively used. Figure 188 is a somewhat simplified diagram of the circuit used in a commercial "short wave" oscillator made by Siemens-Reiniger Werke, which is especially designed for use in high frequency therapy.



Adapted from diagram by Siemens-Reiniger-Werke

FIG. 188. Somewhat simplified connections of the Ultratherm high frequency oscillator

196. Diathermy with Undamped Oscillations. — Valve circuits are now used in much of the modern high frequency equipment in hospitals. In the inductotherm of the General Electric X Ray Corporation for example, a valve oscillator operating at a frequency of 12 million cycles per second is used. High frequency currents are passed through an insulated flexible cable which may be wound around or placed upon various parts of the body. The tissue in the immediate neighborhood of the cable is then heated as a result of induced currents.

In surgical diathermy also valve circuits are of great importance. Laboratory workers who play with high frequency currents of the continuous type soon find out that if the hand or any other part of the body touches the oscillating circuit, there is a slight spark accompanied by a burn at the spot where the spark strikes the flesh. This burn is made evident not only by the unpleasant sensation but also by a smell of seared tissue. By having a

rapidly oscillates above and below a mean value fluctuations of the same frequency will occur in the plate circuit.

195 Generation of Undamped Oscillations. — Suppose a circuit is arranged as in Fig 186. It will be noticed that the loop RLC contains an inductance and a capacity, and consequently, if the resistance is low has a natural frequency of electrical oscillations given by $f = \frac{1}{2\pi\sqrt{CL}}$. If, for

any reason a movement of charges is started in such a circuit and, in consequence, a small charge is given to the condenser this loop should oscillate with

this frequency. If such a circuit were an independent, separate unit, and not part of an arrangement like Fig 186, these oscillations would be very feeble and would rapidly die out after the manner shown in Fig 177. In Fig 186 however, one side of the condenser of this oscillating circuit is joined to the grid of a triode. If therefore, oscillations are started in the loop RLC (and even the closing of a switch can cause an initial electrical disturbance) the potential of the grid will change with the frequency of the oscillations. These rapid changes in grid

FIG. 186. Circuit to illustrate the principle of retroaction and the use of a valve in generating high frequency currents.

potential cause equally rapid changes in the plate circuit and therefore in the coil L_1 inserted in this circuit.

If, now the coil L_1 is placed near the coil L , that is, is *coupled* with it, electromotive forces of the same frequency as the frequency of the plate current changes are induced in L . These electromotive forces (if the coils are suitably wound with respect to each other) reinforce the oscillations originally started in the circuit RLC . The reinforced oscillations cause greater potential changes in the grid hence changes of greater magnitude in the plate current, hence induced electromotive forces of still greater intensity in the original oscillating circuit. There is, therefore, a cumulative effect which results in the maintenance of continuous oscillations. "It is possible to increase the effect of this induction sufficiently to make full

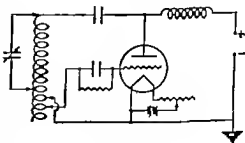
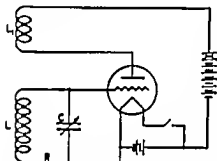


FIG. 187 Connections for the Hartley oscillator

perhaps give some help. From what has been stated above it follows that (1) at any given point in space as time goes on the electric field and the associated magnetic must change their direction with a frequency which is the same as that of the original oscillating circuit and (2) at any given instant, places where the electric field (or the magnetic) is in one direction must alternate with other places where this field is in the opposite direction. In other words, there is the periodicity in time and in space which characterizes a wave motion.

Since the velocity of electromagnetic waves is 3×10^{10} cm per sec. the wave length corresponding to a frequency of a million cycles per second is equal to $\frac{3 \times 10^{10}}{10^6}$ or 3×10^4 cm. or 300 meters. This is within the range of wave lengths used in the ordinary broadcasting band. Much shorter wave lengths and hence much higher frequencies are used in the short wave oscillations found in hospitals. In the oscillator to which Fig 188 applies, for example, the wave length of the emitted radiation is 6 meters. Actually, as we have already indicated in Table XVIII the range of wave lengths generated by purely electrical means extends from those miles in length to others shorter than a millimeter.

Associated with these are the other radiations which have been discussed in some detail in this book. Infrared, visible light, ultraviolet, x rays and gamma rays all belong to the big family of electromagnetic waves. Differing widely in their properties, fundamentally they are all periodic electric and magnetic disturbances which travel in free space at the same velocity. The universe it would appear is alive with radiation which both gives and destroys life.

metallic electrode suitably connected with the high frequency circuit, surgical use can be made of such burns in cauterizing and in coagulating tissue. In urology, for example, high frequency electrodes, themselves comparatively cool are regularly used in surgical treatment.

197 The Generation of Electric Waves.—From his elementary work in physics the student will recall that, if a particle at the end of a line of elastically connected particles is made to oscillate a wave disturbance moves along the line. In general, waves spread out from a vibrating source in any medium in which the particles are so connected that a displacement of a particle disturbs its neighbor. Moreover, λ the wave length f the frequency of the oscillating source, and v the velocity of the wave disturbance are connected by the fundamental wave equation

$$v = f\lambda$$

or
$$\lambda = \frac{v}{f}$$

Consider now the rapid high frequency currents which take place in a coil such as L_1 Fig 183. When a current flows in a wire, it is surrounded by a magnetic field, the direction of the magnetic lines depending on the direction of the current. The oscillating currents in the coil L_1 , therefore, give rise to an oscillating magnetic field about the coil. But, whenever we have a varying magnetic field, an induced E.M.F. results. The rapidly changing magnetic field, therefore, gives rise to a changing E.M.F. of the same frequency. Now Maxwell, the English physicist who was the real founder of wireless telegraphy postulated that, even in a vacuum, such an E.M.F. causes currents which he named *displacement* currents. According to Maxwell's ideas, these displacement currents have a magnetic field associated with them just like ordinary conduction currents in a wire. The varying magnetic field due to the displacement currents then gives rise to new induced E.M.F.; these, in their turn, cause more displacement currents, and so the process continues with the result that an electromagnetic disturbance is propagated from the original region of oscillating currents. All this Maxwell put into mathematical equations by means of which he predicted that the velocity of the electromagnetic disturbance in free space should be the same as that of ordinary light, that is, about 3×10^{10} cm. per sec.

Experimental verification of the truth of Maxwell's prediction was given in 1887 by Hertz, who showed that electric waves were generated by an oscillating circuit of the kind shown in Fig 179 that these waves had many of the properties of light waves and traveled with the same speed. It is not easy to form a picture of electromagnetic waves, but the following ideas will

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APPENDIX

SOME USEFUL CONSTANTS AND CONVERSION FACTORS

1 coulomb	= 3×10^9 statcoulombs
300 volts	= 1 statvolt
1 farad	= 9×10^{11} statfarads
1 microfarad	= 9×10^4 statfarads
1 angstrom	= 10^{-8} cm.
1 micron	= 10^{-4} mm.
1 millimicron	= 10^{-3} mm.
1 X unit	= 10^{-9} angstrom
1 electron-volt	= 1.6×10^{-12} erg
1 electronic unit of charge	{ = 1.60×10^{-19} coulomb = 4.80×10^{-10} statcoulomb
<u>charge on electron</u>	= 1.77×10^9 coulomb per gram
<u>mass of electron</u>	= 1.66×10^{-24} gram
mass of a hydrogen atom	= 9.09×10^{-26} gram
mass of an electron	= 96490 coulomb
charge carried by 1.008 gm. of hydrogen	= 6.56×10^{-17} erg \times sec.
Planck's constant (h)	= $\frac{12354}{\text{maximum voltage}}$ angstroms
shortest wave length	

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TABLE XXXIII — ATOMIC NUMBERS, ATOMIC WEIGHTS AND STABLE ISOTOPES

Element	Symbol	Atomic Number	Atomic Weight	Mass Number of Isotopes
Hydrogen	H	1	1 0080	1 2, 3
Deuterium	D	1	2 0147	
Helium	He	2	4 003	3, 4
Lithium	Li	3	6 940	6, 7
Beryllium	Be	4	9 02	9
Boron	B	5	10 82	10 11
Carbon	C	6	12 010	12, 13
Nitrogen	N	7	14 008	14 15
Oxygen	O	8	16 0000	16, 17 18
Fluorine	F	9	19 00	19
Neon	Ne	10	20 183	20 21 22
Sodium	Na	11	22 997	23
Magnesium	Mg	12	24 32	24, 25 26
Aluminum	Al	13	26 97	27
Silicon	Si	14	28 06	28, 29 30
Phosphorus	P	15	30 98	31
Sulphur	S	16	32 06	32, 33 34 36
Chlorine	Cl	17	35 457	35 37
Argon	A	18	39 944	36, 38, 40
Potassium	K	19	39 096	39 40 41
Calcium	Ca	20	40 08	40, 42, 43, 44, 46, 48
Scandium	Sc	21	45 10	45
Titanium	Ti	22	47 90	46, 47 48, 49 50
Vanadium	V	23	50 93	51
Chromium	Cr	24	52 01	50 52, 53, 54
Manganese	Mn	25	54 93	55
Iron	Fe	26	55 85	54, 56, 57 58
Cobalt	Co	27	58 94	57 59
Nickel	Ni	28	58 69	58 60, 61 62, 64
Copper	Cu	29	63 57	63, 65
Zinc	Zn	30	65 38	64, 66, 67 68, 70
Gallium	Ga	31	69 72	69 71
Germanium	Ge	32	72 60	70, 72, 73, 74, 76
Arsenic	As	33	74 91	75
Selenium	Se	34	78 96	74, 76, 77 78 80, 82
Bromine	Br	35	79 916	79 81
Krypton	Kr	36	83 7	78, 80 82, 83 84, 86
Rubidium	Rb	37	85 48	85 87
Strontium	Sr	38	87 63	84, 86, 87 88
Yttrium	Y	39	88 92	89
Zirconium	Zr	40	91 22	90, 91 92, 94 96
Niobium	Nb	41		93
Molybdenum	Mo	42	95 95	92, 94, 95 96, 97 98 100
Ruthenium	Ru	44	101 7	96, 98 99 100, 101 102, 104
Rhodium	Rh	45	102 91	101 103
Palladium	Pd	46	106 7	102, 104, 105 106, 108 110
Silver	Ag	47	107 880	107 109
Cadmium	Cd	48	112 41	106, 108 110, 111 112, 113, 114, 116

APPENDIX

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Element	Symbol	Atomic Number	Atomic Weight	Mass Number of Isotopes
Indium	In	49	114.76	113, 115
Tin	Sn	50	118.70	112, 114, 115, 116, 117, 118, 119, 120, 122, 124
Antimony	Sb	51	121.76	121, 123
Tellurium	Te	52	127.61	120, 122, 123, 124, 125, 126, 128, 130
Iodine	I	53	126.92	127
Xenon	Xe	54	131.3	124, 126, 128, 129, 130, 131, 132, 134, 136
Cesium	Cs	55	132.91	133
Barium	Ba	56	137.36	130, 132, 134, 135, 136, 137, 138
Lanthanum	La	57	138.92	139
Cerium	Ce	58	140.13	136, 138, 140, 142
Praseodymium	Pr	59	140.92	141
Neodymium	Nd	60	144.27	142, 143, 144, 145, 146, 148, 150
Samarium	Sm	62	150.43	144, 147, 148, 149, 150, 152, 154
Europium	Eu	63	152.0	151, 153
Gadolinium	Gd	64	156.9	152, 154, 155, 156, 157, 158, 160
Terbium	Tb	65	159.2	159
Dysprosium	Dy	66	162.46	158, 160, 161, 162, 163, 164
Holmium	Ho	67	163.5	163
Erbium	Er	68	167.2	162, 164, 166, 167, 168, 170
Thulium	Tm	69	169.4	169
Hafnium	Hf	72	178.6	174, 176, 177, 178, 179, 180
Tantalum	Ta	73	180.88	181
Tungsten	W	74	183.92	180, 182, 183, 184, 186
Rhenium	Re	75	186.31	185, 187
Osmium	Os	76	190.2	184, 186, 187, 188, 189, 190, 192
Iridium	Ir	77	193.1	191, 193
Platinum	Pt	78	195.23	192, 194, 195, 196, 198
Gold	Au	79	197.2	197
Mercury	Hg	80	200.61	196, 198, 199, 200, 201, 202, 204
Thallium	Tl	81	204.39	203, 205
Lead	Pb	82	207.21	204, 206, 207, 208
Bismuth	Bi	83	209.00	209

PROBLEMS AND EXAMINATION QUESTIONS

- 1 Describe a simple experiment to illustrate the difference between an inductive and noninductive circuit.
- 2 Describe with reference to a simple experiment the meaning of the *inductance* of a circuit. What effect has a high inductance when a direct voltage is applied?
- 3 When 110 volts D.C. are applied to the terminals of an electromagnet, the current is 2.5 amp; whereas when 110 volts A.C. are applied the current is only 0.8 amp. Explain clearly the reason for the difference.
- 4 An electromagnet has a resistance of 30 ohms and a reactance of 40 ohms (for A.C. of 60 cycles per sec.) Find (i) the impedance of the electromagnet, (ii) the inductance in henries.
- 5 Distinguish between *impedance* and resistance.
- 6 When 60 cycles per sec. A.C. is used the impedance of a coil is found to be 40 ohms. If the resistance of this coil is 10 ohms, find its inductance in henries.
- 7 The reactance of a coil when used with 60 cycles per sec. A.C. is 50 ohms. Find its inductance.
- 8 What information should be given about the output of a transformer for x ray work?
- 9 In a step-up transformer the secondary has 1000 times as many turns as the primary. When 10 milliamperes are delivered at 100 000 volts, what is the current in the primary circuit? (Assume the transformer 100 per cent efficient.)
- 10 What is the special feature about a synchronous motor?
- 11 What is a rectifying disc and how is it used? Illustrate your answer by a diagram or diagrams.
- 12 By means of a diagram show how the current in the primary of a good induction coil varies with the time. Hence, explain the relative magnitude of the E.M.F. induced in the secondary on make as compared with break.
- 13 Describe, with simple diagrams, the two chief ways of controlling the voltage applied to an x-ray tube.
- 14 Make diagrams illustrating the control of voltage applied to an x ray tube, (i) by rheostat, (ii) by autotransformer. Explain also why the rheostat acts as a kind of safety valve when a "short" develops in the tube circuit.
- 15 How is the voltage across an x ray tube controlled? Make diagrams to illustrate two methods.
- 16 How is the voltage across an x ray tube measured? Describe several means.
- 17 Explain (i) why a voltmeter across the primary of an x ray transformer can be (and often is) marked to read secondary kilovolts; (ii) the objection to this practice.
- 18 Explain fully the meaning of the following portion of a table placed over the control board of an x-ray transformer

Primary Voltage	Autotransformer Button	Tube Voltage	
80	3	10 ma.	30 ma.
90	8	77 kv	72 kv
		88 kv	83 kv

Hence point out the objection to a prereading kilovoltmeter

19 Is air at atmospheric pressure a conductor of electricity? Describe several ways in which air may be made conducting.

20 Describe the variations in the conductivity of a tube with electrodes, as the air is gradually removed, the electrodes being connected to high voltage terminals.

21 What are ions, electrons, cathode rays?

22 Describe how the voltage across a tube (originally containing air at atmospheric pressure) varies as the air is gradually exhausted, if the tube is carrying a current.

23 Describe the properties of cathode rays with reference to suitable experiments to illustrate these properties.

24 What is meant by the *atomic number* of an element?

25 () Explain with the aid of diagrams, a method of generating (i) a narrow beam of cathode rays; (ii) a narrow beam of positive rays; and (iii) a beam of thermionic electrons.

(b) Indicate how positive rays can be used to compare atomic weights.

26 Compare the hot filament x ray tube with the gas x ray tube with respect to (i) degree of vacuum, (ii) origin of electrons, (iii) control of current.

27 What is the chief advantage of a line focus over a circular focal spot whose diameter is equal to the width of the line?

28 What methods are used to keep the target of an x ray tube cool? Why is this desirable?

29 What are two special features of the metallic x-ray tube?

30 Describe very briefly three means which are utilized for keeping down the temperature of the target of a tube.

31 Discuss the blackening of a gas tube with reference to its causes and the means of lessening it.

32 Discuss the relation of the size of the focal spot to (a) the power which may be supplied a tube, (b) the character of the radiographs taken, (c) the question of treatment.

33 Why should a target be of high atomic weight?

34 When a hot filament tube is in good condition and 100 000 volts are applied across its terminals, the filament circuit out of which should the milliamperage meter read? If in such a case glow were observed in the bulb, what conclusion would you draw?

35 What is meant by saturation tube current?

36 What effect has increasing the voltage across a hot filament tube on the tube current? What effect in the case of a gas tube?

37 What connection is there between the focal spot and the input of an x ray bulb? Why may much larger x ray tube currents be used for a short time than for long periods?

38 Describe as fully as you can the essential features of a good modern x ray tube suitable for general diagnostic work.

39 What are the special features of the Chaoval therapy tube?

40 What is the special advantage or advantages of the rotating anode tube?

41 Make a diagram to illustrate the principle of a stabilizer by means of which a hot filament tube current may be kept constant.

42 A slight increase in the voltage applied to a Coolidge tube in general does not change the tube current, whereas a slight change in the filament current may cause a marked change in the tube current. Explain the reasons.

43 Make a fully labeled diagram of the electrical connections in an x ray tube outfit which utilizes the following features (i) autotransformer control; (ii) a four valve rectifying arrangement (the Graetz circuit); (iii) a hot filament x ray tube; (iv) a filament current ammeter (for x ray tube); and (v) a milliammeter in tube circuit.

Indicate by arrows the current path in the tube circuit during one half-cycle.

44 Explain, with the aid of simple diagrams, the difference between *self-rectification*, *half-wave rectification*, and *full-wave rectification*.

45 Why is a rectifier desirable in operating a standard universal Coolidge tube but not necessary for the radiator Coolidge tube?

46 Under what circumstances can a very high vacuum be made conducting? Describe the mode of conduction.

47 Explain by means of a simple diagram, the use of (i) a mechanical rectifier for high tension voltages, (ii) a single valve hot filament rectifier. What is the difference in the nature of the tube currents for the two cases?

48 With the aid of diagrams describe and explain a rectifying circuit for an alternating high tension voltage; (i) using every half-cycle, by means of a single valve and a condenser; and (ii) using alternate half-cycles, but (approximately) doubling the transformer voltage.

49 A hot filament tube, whose filament is heated by a step-down transformer is operated by a high-tension transformer with autotransformer control and with a Villard rectifying arrangement. Make a complete diagram of the electrical system.

50 A condenser of capacity $1/10$ microfarad is charged to 200 000 volts. It then maintains an average current of 10 ma. through an x ray tube for $1/100$ second. Find the voltage across the condenser at the end of this time.

51 With the aid of two diagrams, one for each half-cycle, show how a condenser may be combined with a single rectifying valve and transformer to maintain an approximately steady voltage across an x-ray tube.

52 Make a diagram showing the essential connections when an x ray tube is operated by a transformer rectified by a Greinacher circuit.

53 What effect has the speed of cathode rays on the nature of the x ray beam originating when the rays are stopped?

54 Describe a simple experiment to show that in general a beam of x rays consists of a mixture of hard and soft.

55 Explain the purpose of an intensifying screen, as well as the principle underlying its use.

56 Describe six properties of x rays.

57 Describe two applications of the fluorescence excited by x-rays in radiology.

58 How would you test an x ray beam (without using a spectrometer method) to see whether it is homogeneous, or not?

59 A homogeneous beam of x-rays has a penetrating power such that the half absorption value of aluminum is 2 mm. How much will the intensity of such a beam be reduced by 8 mm. of aluminum?

60 The intensity of a filtered beam of x-rays is examined before and after passing through layers of aluminum 1 mm., 2 and 3 mm. thick and ionization values of 100, 80, 64 and 41.2 are obtained. (i) Is this beam homogeneous and if so, why? (ii) What is the H.V.L.?

61 Explain what is meant by H.V.L.

62. What is the general effect of a filter on a beam of x-rays?

63. (i) Describe fully how you would photograph the ultraviolet and visible spectrum emitted by any source of light. (ii) Compare the spectrum you would obtain with a carbon arc and that from a quartz mercury vapor lamp. (iii) If your source of light was sunlight, what would be the approximately shortest wave length recorded (in angstroms) (1) through an open window (2) through a closed window of ordinary glass. In each case explain why no shorter wave lengths are recorded.

64. Describe with diagram the spectrometer method of measuring in angstroms the constituent wave lengths in a beam of x rays. Indicate on what two quantities the magnitude of the calculated wave length depends.

65. A beam of x rays, consisting of both general and characteristic rays, is analyzed with an ionization chamber and a spectrometer. Indicate the nature of the graph you would obtain. If a photographic method were used what results would you obtain?

66. Explain why the Seeman spectrograph can be used as a voltmeter.

67. An x ray tube is operated on 150 000 volts. What is the shortest wave length emitted?

68. If the analysis of an x-ray beam showed the shortest wave length to be 0.1 angstrom units, what maximum voltage is applied to the tube?

69. Why can an x ray spectrometer be used as a high tension voltmeter? An x-ray tube is operated at a constant voltage. Draw a rough graph to illustrate the character of the rays emitted. If the voltage = 200 000 what will the shortest wave length be?

70. What is meant by the effective wave length of an x ray beam? Explain the fundamental principle involved in its determination by means of a Duane standard graph.

71. Show by a graph the distribution in intensity of x rays with wave length when a tube is operated at constant potential. Indicate any differences that you might expect if the operating voltage were changed from say 50 000 volts to 200 000 volts.

72. Describe two ways of obtaining x-rays characteristic of the matter from which they are emitted.

73. A very penetrating primary beam of x-rays traverses a layer of matter containing both heavy and light elements, and an observer with suitable apparatus, examines all possible secondary emissions from the matter in a direction at right angles to the primary beam. State, with brief explanations, what he observes.

74. Explain what scattered x-rays are, and discuss their importance in radiography.

75. Distinguish between scattered and characteristic fluorescent secondary x rays.

76. Describe an experiment to demonstrate the existence of secondary x rays.

77. Describe an experiment to enable you to find the relative intensities of the primary beam and of the secondary rays, at a given place in a medium traversed by a beam of x rays.

78. Discuss the importance of scattered rays in radiography and show how their harmful effects may be minimized by the use of a Bucky Diaphragm.

79. Explain the construction of a Potter Bucky Diaphragm. State why it is used and under what conditions.

80. A beam of x rays traverses a layer of matter. Discuss what happens to the beam.

81. What is meant by the *critical absorption wave length* of an absorbing substance? Why is a knowledge of its value important in choosing a filter?

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61 Explain what is meant by H.V.L.

5 divisions per second. When a condenser is attached to the insulated rod of the electroscope, and an x ray beam of equal intensity is used it takes one hour for the leaf to fall 25 divisions. Find the capacity of the condenser.

96 Describe an experiment to show that in deep therapy scattered rays may be the cause of a greater intensity at the place treated than the primary beam.

97 The natural leak of an electroscope of capacity 10 statfarads is 0.5 divisions per minute. Find the natural leak, if the insulated plate of a condenser of capacity 200 statfarads is attached to the insulated system of the electroscope, the outer case of the electroscope and the other plate of the condenser being grounded.

98 In a standard ionization chamber ions are driven to a collecting electrode from a volume of 10 c.c. The capacity of the electrode and attached electrometer system is 100 statfarads. If the intensity of the x ray beam is 0.4 units per second, find the change of potential (in volts) of the electrometer system in 5 minutes. (1 farad = 9×10^{11} statfarads.)

99 Make a diagram showing how a small ionization chamber can be used in connection with an electroscope. Indicate what parts are insulated and what grounded.

100 Define the roentgen and show with diagram, how by means of a standard ionization chamber the intensity of a beam in units per second may be found.

101 Explain what constitutes a good "phantom" for x rays in therapy and name one suitable substance.

102 In deep therapy why is a filter always used between the patient and the target of the tube?

103 (a) An electroscope is joined to the insulated plate of an x ray standard parallel plate ionization chamber (whose other plate is grounded) and the insulated system, whose capacity is 1/1000 microfarad, is charged until its potential is 900 volts. (i) What is the total charge in coulombs on the insulated system? (ii) A parallel beam of x rays passes between the plates of the chamber and ions are driven to the insulated plate from a volume of 50 c.c. If the intensity of the beam of x rays is 1 roentgen per second, find how long it will take to discharge the electroscope (and attached plate)

$$1 \text{ microfarad} = 900,000 \text{ statfarads}; \quad 300 \text{ volts} = 1 \text{ statvolt};$$

$$1 \text{ coulomb} = 3 \times 10^9 \text{ statcoulomb.}$$

104 In an ionization chamber why must the voltage between the two electrodes exceed a certain minimum amount?

105 A tube 10 cm. bel w the surface is treated under the following conditions: Port of entry = 25 cm; Voltage across tube = 200 Kv; Tube current = 5 ma.; Filter = 0.75 mm. Cu + 1 mm. Al; Target-skin distance = 30 cm.; Effective wave length = 0.15 A.U; Percentage of surface intensity = 40 per cent. Discuss the importance of each factor.

106. Discuss the importance of the size of the port of entry in using x rays for therapy.

107 Explain the meaning of "millicurie of radium emanation."

108 What radiations are given off from a tube of radium emanation enclosed in a tube of platinum 0.5 mm. thick?

109 If at a certain time you were provided with 100 millicuries of radium emanation, how much would you have after 48 hours?

110 A radium emanation tube sent from New York to Kingston had a strength of 100 millicuries when it left New York. (i) What is its strength when used in King-

82 Explain with reference to a suitable graph what is meant by *critical absorption wave length*. What importance has this in filtration?

83 Explain why lead is not a suitable material to use as an x ray filter

84 How does the penetration in copper of x rays of wave length 0.15 A.U. compare with those of 0.25 A.U.?

85 What is meant by (a) a monochromatic beam of x rays, (b) characteristic x rays, (c) independent or general x rays?

86 A homogeneous radiation is reduced in intensity 50 per cent by a thickness of 0.5 mm. of copper. (a) Plot a graph showing how the intensity falls off with increasing thicknesses of copper. (Note—Obtain 5 points on your graph, using copper thicknesses of 0.5 1.5, 2.0 2.5 and 3.0 mm.) (b) What is the name given to this type of graph? Give two examples of radiations whose absorption is governed by a graph of this kind. (c) Find the *linear absorption coefficient* for the above radiation. (d) If the density of copper is 8.9 grams per c.c., find the *mass absorption coefficient*. (e) Without carrying out the actual calculations show how you would find the emergent intensity for a layer of copper 2.6 mm. thick.

87 A parallel beam of x rays of wave length 0.080 A. enters an ionization chamber and its intensity is found to be 100. (a) Find the intensities when one mm. sheets of Al, Cu, and Pb are in turn interposed in the beam. The densities are 2.70 8.93 and 11.37 gm./c.c., respectively and the mass absorption coefficients are 0.143 0.263 and 2.47 respectively. *Ans* 96.2 79.1 6.06 (b) Find the thicknesses of Al, Cu, and Pb which will reduce the intensity of the beam of wave length 0.080 A. to half-value when interposed in turn. *Ans* 13.0 2.95 0.247 mm.

88 (a) Make a diagram showing the electric connections when a standard ionization chamber and a galvanometer are used to compare the intensities of x ray beams.

(b) If in a standard chamber ions were taken from a volume of 10 c.c. and a current of 10^{-8} ampere was recorded by a galvanometer what is the intensity of the beam in *r* units per second?

89 Why must a small ionization chamber be calibrated by means of a standard chamber if measurement in *r* units is required?

90 How does the intensity of a beam of x rays at a given place depend on (a) the distance from target (b) the voltage across the tube, (c) the tube current?

91 When a small ionization chamber (joined to an electroscope) is placed in a beam of x rays at a place 25 cm. from the focal spot, the electroscope falls at the rate of 2.1 divisions per second. What is the rate of fall if the chamber is removed to a distance of 60 cm.?

92 A steadily increasing voltage is applied to two plates between which a narrow strip of air is kept ionized by a beam of x rays of constant intensity. Describe, with simple graph and explanation, how the current between the plates alters with the voltage.

93 How would you show experimentally that water is a good phantom for tissue?

94 A small ionization chamber is used to measure the intensity of an x ray beam at a certain focal target distance, (i) in air (ii) when the chamber rests on a thick block of paraffin, (iii) when the chamber is completely surrounded by paraffin. Intensities of 23.43 and 35 units are obtained. Discuss and explain these results.

95 The insulated electrode of an ionization chamber is joined to an electroscope, the capacity of the system being 10 e.s.u. units. When an x ray beam of a certain intensity ionizes the air in the chamber the leaf of the electroscope falls at the rate of

two products. By writing down the transformation equation show what the other product must be. (b) Why is the term *radiophosphorus* used?

125 ^{32}P and protons are obtained when a certain element is bombarded with neutrons. Find the atomic weight and the atomic number of this element.

126 (a) Discuss as fully as you can the passage of neutrons through matter describing the various interactions of the neutrons and atoms which may occur. Where possible make specific reference to tissue. (b) Write the reaction equation for one method that has been used to obtain neutrons in abundance. (c) What protection would you use against a powerful source of neutrons?

127 (a) Radiophosphorus ^{32}P is produced in the following ways, in each of which the bombarding particle is absorbed (i) sulphur (atomic number 16, mass number 32) is bombarded with neutrons, (ii) chlorine (atomic number 17 mass number 35) is bombarded with neutrons, (iii) phosphorus (atomic number 15 mass number 31) is bombarded with deuterons, (iv) silicon (atomic number 14 mass number 29) is bombarded with alpha particles. Write the equations for these reactions. (b) What radiation is emitted by ^{32}P and what is its half-period?

128 (a) Explain fully how bombarding alpha particles were used in the experiment which led to the discovery of neutrons. (b) Neutrons are sometimes produced by the bombardment of the lithium isotope of mass number 7 by high speed deuterons. Write down the probable transformation equation. (c) Explain one method of manufacturing radioactive sodium.

129 A charged condenser is discharged through a spark gap. (i) What is the nature of the discharge current? (ii) On what does the *intensity* of the discharge current depend?

130 When a condenser discharges through a low resistance and oscillations result, in what way does the frequency of the oscillations depend on the capacity of the condenser?

131 Describe a simple arrangement for obtaining damped high frequency currents. Explain how (i) the frequency (ii) the intensity is altered.

132 High frequency oscillations are set up in a circuit of negligible resistance containing a condenser of capacity 0.001 microfarad and an inductance of 0.00002 henry. Calculate the frequency in cycles per second.

INTERNATIONAL RECOMMENDATIONS FOR X RAY AND RADIUM PROTECTION*

Revised by the International X Ray and Radium Protection Commission at the Fifth International Congress of Radiology Chicago, September 1937

International Recommendations

1 The dangers of overexposure to x rays and radium can be avoided by the provision of adequate protection and suitable working conditions. It is the duty of those in charge of x ray and radium departments to insure such conditions for their personnel. The known effects to be guarded against are

- (a) Injuries to the superficial tissues;
- (b) Changes in the blood and derangements of internal organs, particularly the generative organs.

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ton for treatment 48 hours later? (ii) After what time will its strength be 50 millicuries? (iii) After what approximate time will a 10 milligram tube of radium *salt* fall to half value?

111 The same type of curve is obtained when the decrease in the activity of radon is plotted against time as when the decrease in the intensity of a homogeneous beam of x rays is plotted against the thickness of an absorbing layer of matter. Indicate the general nature of this curve, explaining the law which defines it.

112 On a certain day a radium emanation tube causes the leaf of an electroscope to fall at the rate of 60 divisions per minute. How fast will the same tube (at the same place) cause the leaf to fall (i) after 24 hours, (ii) after 48 hours?

113 If all the radon is collected every *second* day from 1 gram of radium, find the strength in millicuries of the amount collected, on the day collection is made.

114 An 0.1 gram of radium emanation is left standing in solution for at least a month. The accumulated radium emanation is then drawn off each day for three successive days, and each day sealed in a single tube. Find the strength of the three tubes on the third day.

115 Explain what is meant by the half period of a radioactive substance, and describe all the steps you would take to measure this constant for thorium emanation.

116 If a gram of radium was the total amount in an emanation plant, what is the maximum number of 20 millicurie tubes which could be obtained from this plant at one time? (i) About how long would it be necessary to wait before collecting the emanation to obtain this maximum number? (ii) What would be the strength of one of the 20 mc. tubes 24 hours after it was removed from the plant?

117 A radium emanation plant, with 1 gram of radium in solution, has all the active gas removed on a certain day. Work out how many millicuries could be taken from the plant on the next removal which takes place after an interval of three days.

118 Radium D has an atomic number of 82 and an atomic weight of 210. On emitting beta and gamma rays it changes into radium E, which in its turn also emits beta and gamma rays, changing into polonium. Finally polonium emits alpha rays, changing into lead. Show that lead and radium D are isotopes and find from the above data, the atomic weight of lead.

119 The atomic weight of radium is 226, and its atomic number is 88. If the final stable product after the successive transformations of radium is lead, of atomic weight 206 and atomic number 82 find the total number of (i) alpha particles emitted, (ii) beta particles, by the time a single radium atom has turned into an atom of lead.

120 *Enumerate (without description)* three ways of obtaining voltages of the order of 50 000 and one way of obtaining 1 000 000 volts.

121 With reference to the equation



explain (i) what experimental fact this tells you; (ii) the meaning of the subscript and superscript numbers; (iii) why ${}_{11}\text{Na}^{24}$ is called radio-sodium.

122. What is the difference between stable and unstable isotopes? Give one example of each class.

123 Write down the transformation equation when radio-sodium is formed by the bombardment of magnesium (atomic weight = 24; atomic number = 12) by neutrons.

124 When sulphur (atomic weight 32 atomic number 16) is bombarded with nuclei of heavy hydrogen, radiophosphorus (atomic weight 30 atomic number 15) is one of

two products. By writing down the transformation equation, show what the other product must be. (b) Why is the term *radiophosphorus* used?

125 uP^{32} and protons are obtained when a certain element is bombarded with neutrons. Find the atomic weight and the atomic number of this element.

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(i) Injuries to the superficial tissues;

(ii) Changes in the blood and derangements of internal organs, particularly the generative organs.

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The evidence at present available appears to suggest that under satisfactory working conditions, a person in normal health can tolerate exposure to x rays or radium gamma rays to an extent of about 0.2 international roentgen (r) per day or $1r$ per week. On the basis of continuous irradiation during a working day of seven hours, this figure corresponds to a tolerance dosage rate of $10^{-5}r$ per second. The protective values given in these recommendations are generally in harmony with this figure under average conditions.

I. WORKING HOURS, ETC.

2 The following working hours, etc., are recommended for whole-time x-ray and radium workers:

- (a) Not more than seven working hours a day in temperate or cold climates. For workers in tropical climates, shorter hours may be desirable.
- (b) Not more than five working days a week; the off-days to be spent as much as possible out of doors.
- (c) Not less than four weeks' holiday a year preferably consecutively.
- (d) Whole-time workers in hospital x ray and radium departments should not be called upon for other hospital service.
- (e) X ray and particularly radium workers, should be systematically submitted, both on entry and subsequently at least twice a year to expert medical, general, and blood examinations, special attention being paid to the hands. These examinations will determine the acceptance, refusal, limitation, or termination of such occupation.
- (f) The amount of radiation received by operators should be systematically checked to insure that the tolerance dose is not exceeded. For this purpose, photographic films or small-capacity condensers may be carried on the person.

II. GENERAL X RAY AND RADIUM RECOMMENDATIONS

3 X ray departments should not be situated below ground-floor level.

4 All rooms, including dark rooms, should be provided with windows affording good natural lighting and ready facilities for admitting sunshine and fresh air whenever possible.

5 All rooms should be provided with adequate exhaust ventilation. In certain climates it may be necessary to have recourse to air conditioning. For rooms of normal dimensions, say 3 000 cubic feet (90 c. meters) in which corona free apparatus is installed, the ventilating system should be capable of renewing the air of the room not less than six times per hour while up to ten times may be required when the apparatus is not corona free. Large rooms require proportionately fewer changes of air per hour than small ones. Air inlets and outlets should be arranged to afford cross-wise ventilation of the room.

6. All rooms should preferably be decorated in light colors.

7 A working temperature of about 18–22 C. (65–72 F) is desirable in x ray rooms.

8 X ray rooms should be large enough to permit a convenient layout of the equipment. A minimum floor area of 250 sq. ft. (23 sq. meters) is recommended for x ray rooms, and 100 sq. ft. (10 sq. meters) for dark rooms. Ceilings should be not less than 11 ft. (3.5 meters) high.

9 High tension generators employing mechanical rectification should preferably be placed in a separate room from the x-ray tube.

III. X RAY PROTECTIVE RECOMMENDATIONS

10 An x-ray operator should on no account expose himself to a direct beam of x-rays.

11 An operator should place himself as remote as practicable from the x ray tube. It should be borne in mind that valve tubes are capable of producing x rays.

12 The x-ray tube should be self-protected, or otherwise surrounded as completely as possible, with protective material of adequate lead equivalent.*

13 The following lead equivalents are recommended under average conditions:

X-rays Generated by Peak Voltages	Minimum Equivalent Thickness of Lead
Not exceeding 75 kv	1 mm.
100	1 5
125	2
150	2 5
175	3
200	4
250	6
300	9
350	12
400	15
(600)	(35)

(4) *Diagnostic Work.*—14 In the case of diagnostic work with other than completely protected tubes, the operator should be afforded additional protection from stray radiation by a screen of a minimum lead equivalent of one millimeter.

15 Screening examinations should be conducted as rapidly as possible with minimum intensities and apertures, particularly when fractures are reduced under x-rays. Palpitation with the hand should be reduced to the minimum.

16. The lead glass of fluorescent screens should have the protective values recommended in paragraph 13.

17 In the case of screening stands, the fluorescent screen should, if necessary be provided with a protective "surround" so that adequate protection against direct radiation is afforded for all positions of the screen and diaphragm.

18 Screening stands and couches should provide adequate arrangements for protecting the operator against scattered radiation from the patient.

19 Protective gloves, which should be suitably lined with fabric or other material should have a protective value not less than one third millimeter lead throughout both back and front (including fingers and wrist). Protective aprons should have a minimum lead value of one half millimeter.

(8) *Treatment.*—20 In the case of x ray treatment the operator is best stationed completely outside the x ray room behind a protective wall, the lead equivalent of which will depend on the circumstances. In the case of a single x-ray tube excited by voltages up to 200 kv., the protective wall should have a minimum lead equivalent

* The lead equivalent of a given thickness of protective material is that thickness of lead which is equally opaque to x rays excited at some specified peak voltage.

of two millimeters. This figure should be increased in the case of higher exciting voltages or of heavy tube currents or if the protective value of the x ray tube enclosure falls short of the value given in paragraph 13. In such event the remaining walls, floor and ceiling may also be required to provide supplementary protection for adjacent occupants to an extent depending on the circumstances. Full protection should be provided in all those directions in which the direct beam can operate.

Inspection windows in screens and walls should have protective lead values equivalent to that of the surrounding screen or wall.

21 In those cases in which an x ray tube is continuously excited and treatment periods are regulated by means of a shutter some form of remote control should be provided for the shutter to insure that the operator is not exposed to direct radiation while manipulating the shutter or filter.

22 Efficient safeguards should be adopted to avoid the omission of a metal filter in x ray treatment for example, by an interlocking device or by continuously measuring the emergent radiation. Protective screens and applicators (cones) used in treatment to define the ports of entry of x ray beams should be sufficiently thick to reduce the dosage rate outside the direct field of irradiation to less than 10^{-3} roentgen per second.

IV ELECTRICAL PRECAUTIONS IN X RAY ROOMS

23 The floor-covering of the x ray rooms should be insulating material such as wood, rubber or linoleum.

24 Where permanent overhead conductors are employed they should be not less than 9 feet (3 meters) from the floor. They should consist of stout metal tubing or other coronaless type of conductor. The associated connecting leads should be of coronaless wire kept taut by suitable rheophores.

25 Wherever possible, earthed guards or earthed sheaths should be provided to shield the more adjacent parts of the high tension system. Unshielded leads to the x ray tube should be in positions as remote as possible from the operator and the patient. The use of "shockproof" x ray equipment, in which the high tension circuit is completely enclosed in earthed conductors, is recommended. In all cases, however indiscriminate handling of x ray tubes during operation should be forbidden. Unless there are reasons to the contrary metal parts of the apparatus and room should be efficiently earthed.

26 Main and supply switches should be very accessible and distinctly indicated. They should not be in the proximity of the high tension system, nor should it be possible for them to close accidentally. The use of quick-acting, double-pole circuit breakers is recommended. Overpowered fuses should not be used. If more than one apparatus is operated from a common generator suitable high tension, multiway switches should be provided. In the case of some of the constant potential generators, a residual charge is held by the condensers after shutting down, and a suitable discharging device should, therefore, be fitted. Illuminated warning devices which operate when the equipment is "alive" serve a useful purpose. The staff should be trained in the use of first-aid instructions dealing with electrical shock. If foot switches are used they should be connected in series with an ordinary switch and should be so designed that they cannot be locked to keep the circuit "alive" and are not capable of being closed accidentally.

27 Some suitable form of kilovoltmeter should be provided to afford a measure of the voltage operating the x-ray tube.

28 Low flashpoint anaesthetics should never be used in conjunction with x rays.

V FILM STORAGE PRECAUTIONS

29 The use of noninflammable x ray films is strongly recommended. In the case of inflammable films, suitable precautions should be taken as regards their use and storage. Large stocks should be kept in isolated stores, preferably in a separate building or on the roof.

VI. RADIUM PROTECTIVE RECOMMENDATIONS

(A) *Radium Salts* — 30 Protection for radium workers is required from the effects of

(a) Beta rays upon the hands;

(b) Gamma rays upon the internal organs, vascular and reproductive systems.

31 In order to protect the hands from beta rays, reliance should be placed, in the first place, on distance. The radium should be manipulated with long handled forceps, and should be carried from place to place in long-handled boxes, lined on all sides with at least one centimeter of lead. All manipulations should be carried out as rapidly as possible.

32. Radium, when not in use, should be stored in a safe as distant as possible from the personnel. It is recommended that the safe should be provided with a number of separate drawers individually protected. The amount of protection should correspond to the values given in the following table. These values, which are based on working conditions where there is proximity to radium may be reduced for larger working distances.

Maximum Quantity of Radium Element	Thickness of Lead
0.05 gm.	5 cm.
0.2	8.5
0.5	10
1.0	11.5
2.0	13
5.0	15
10.0	17

33 A separate room should be provided for the "make-up" of screened tubes and applicators, and this room should be occupied only during such work.

34 In order to protect the body from the penetrating gamma rays during the handling of radium, a screen of not less than 2.5 centimeters of lead should be used, and proximity to the radium should occur only during actual work, and for as short a time as possible.

35 The measurement room should be a separate room, and it should preferably contain the radium only during its actual measurement.

36. Nurses and attendants should not remain in the same room as patients undergoing radium treatment with quantities exceeding one-half gram.

37 All unskilled work, or work which can be learned in a short period of time, should preferably be carried out by temporary workers, who should be engaged on such work for periods not exceeding six months. This applies especially to nurses and those engaged in "making up" applicators.

38 Radium containers should be tested periodically for leakage of radon. Prejudicial quantities of radon may otherwise accumulate in radium safes, etc., containing a number of leaky containers.

39 Discretion should be exercised in transmitting radium salts by post. In the case of small quantities (less than 10 mg of radium element) it is recommended that the container should be lined throughout with lead not less than three millimeters thick, while for quantities between 10 and 50 mg of radium element, the lead container should be supported in the center of a box with a minimum dimension of 30 cm. Packages containing more than 50 mg of radium element are preferably sent by rail or hand under suitable conditions of protection.

(B) *Radon*.—40 In the manipulation of radon, protection against beta and gamma rays is required and automatic or remote controls are desirable.

41 The handling of radon should be carried out, as far as possible, during its relatively inactive state.

42 Precautions should be taken against excessive gas pressures in radon plants. The escape of radon should be very carefully guarded against, and the room in which it is prepared should be provided with an exhaust fan controlled from outside the room.

43 Where radon is likely to come in direct contact with the fingers, thin rubber gloves should be worn to avoid contamination of the hands with active deposit. Other wise, the protective measures recommended for radium salts should be carried out.

44 The pumping room should preferably be contained in a separate building. The room should be provided with a connecting tube from the special room in which the radium is stored in solution. The radium in solution should be heavily screened to protect people working in adjacent rooms. This is preferably done by placing the radium solution in a lead-lined box, the thickness of lead recommended being according to the table in paragraph 32.

(C) *Radium-beam Therapy*.—45 The risks to the operator attendant on the use of large quantities of radium in radium-beam therapy may be largely obviated if some system of remote control is adopted by which the radium is only introduced into the "bomb" after the latter has been adjusted in position on the patient. If such arrangements are not available, the importance of expeditious handling is stressed.

46 Rooms used for radium-beam therapy should provide adequate protection for adjacent wards and rooms in permanent occupation.

The following minimum lead thicknesses are required to secure a tolerance dosage rate of 10^{-5} roentgen per second at various distances from different quantities of radium.

The distances corresponding to the tolerance dosage rate in the absence of lead are also given.

Quantity of Radium Element (0.5 mm. Pt screen)	Thickness of Lead to Give Tolerance Dosage Rate at the Following Distances from Radium Source				Tolerance Distance with no Lead
	50 cm.	1 meter	2 meters	5 meters	
gm.	cm.	cm.	cm.	cm.	meters
1	9 0	6 0	3 0		4 5
2	10 5	7 5	4 5	1 0	6 5
5	12 5	9 5	6 5	2 5	10 5
10	04 0	11 0	8 0	4 0	14 5

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43 Where radon is likely to come in direct contact with the fingers, thin rubber gloves should be worn to avoid contamination of the hands with active deposit. Other wise, the protective measures recommended for radium salts should be carried out.

44 The pumping room should preferably be contained in a separate building. The room should be provided with a connecting tube from the special room in which the radium is stored in solution. The radium in solution should be heavily screened to protect people working in adjacent rooms. This is preferably done by placing the radium solution in a lead-lined box, the thickness of lead recommended being according to the table in paragraph 32.

(C) *Radium-beam Therapy*.—45 The risks to the operator attendant on the use of large quantities of radium in radium-beam therapy may be largely obviated if some system of remote control is adopted by which the radium is only introduced into the "bomb" after the latter has been adjusted in position on the patient. If such arrangements are not available, the importance of expeditious handling is stressed.

46 Rooms used for radium-beam therapy should provide adequate protection for adjacent wards and rooms in permanent occupation.

The following minimum lead thicknesses are required to secure a tolerance dosage rate of 10^{-8} roentgen per second at various distances from different quantities of radium.

The distances corresponding to the tolerance dosage rate in the absence of lead are also given.

Quantity of Radium Element (0.5 mm. Pt screen)	Thickness of Lead to Give Tolerance Dosage Rate at the Following Distances from Radium Sources				Tolerance Distance with no Lead
	50 cm.	1 meter	2 meters	5 meters	
gm.	cm.	cm.	cm.	cm.	meters
1	9 0	6 0	3 0		4 5
2	10 5	7 5	4 5	1 0	6 5
5	12 5	9 5	6 5	2 5	10 5
10	04 0	11 0	8 0	4 0	14 5

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